JOINT EUROPEAN TORUS

JET JOINT UNDERTAKING

ANNUAL REPORT 1996

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EUR-JET-AR19

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MAY 1997

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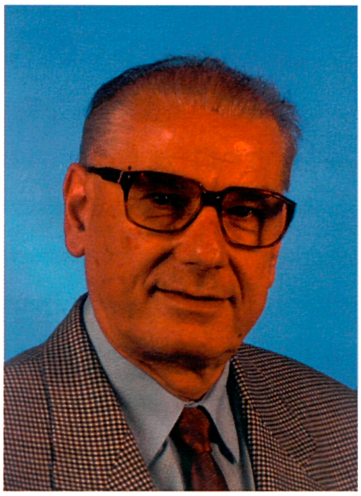
Preface



Before 1996, JET had already completed the Pumped Divertor Characterisation Phase of its programme, which had addressed the central problems of the International Thermonuclear Experimental Reactor (ITER) divertor: efficient dissipation of the exhausted power; control of particle fluxes; and effective impurity screening.

At the beginning of 1996, JET entered the ITER-EDA Support Phase of its programme. The machine was then in shutdown for installation of the Mark II support structure and the Mark IIA divertor target assembly, which were successfully completed on schedule. The Mark II support structure will be the basis for all future divertor work at JET and is the key to the JET programme to 1999.

During this shutdown, preparations were also made for the next period of deuterium-tritium operation, scheduled for mid-1997, and for a subsequent shutdown to replace the Mark IIA target structure by remote handling without manned intervention. This remote handling operation will demonstrate for the first time one of the central technologies required both for ITER and for a fusion reactor. In addition, thirty three carriers and associated tiles were successfully installed by remote handling, providing confidence in the operational procedures, tooling, equipment, support management and time estimates for this important procedure. The shutdown was completed on schedule at the end of March 1996.

Plasma impurities have always been a major obstacle to reactor-relevant, steady state operation. JET's programme has aimed to establish reliable methods of plasma purity control and plasma exhaust and, for this purpose, a pumped divertor was installed to test various configurations. Tests on the first divertor configuration (Mark I) were successfully completed during 1995. The 1996 experimental campaign concentrated on specific ITER-relevant issues related to the "more-closed" Mark IIA divertor. The scientific results obtained showed that the Mark IIA divertor offered improved power handling over the Mark I divertor, pumped the plasma 2-3 times more rapidly and showed signs of increased neutral recycling in the divertor region.

The 1996 experimental campaign also concentrated on the scaling of the H-mode threshold power and the energy confinement, in view of their importance for predicting ITER's ignition margin and fusion power output. The threshold power for the H-mode was found to be independent of the type of additional heating used, and, in conjunction with the US tokamak D-IIID, confinement in the plasma core was shown to depend on three dimensionless parameters (normalised Larmor radius, collisionality and plasma pressure). Precise experiments showed that the dependence on the first two of these parameters was in accordance with the scaling law used at present for ITER, but the plasma pressure dependence may be more favourable. On the other hand. with increasing radiated power to reduce the heat load to the divertor target plates, confinement degrades progressively and is less favourable than the ITER scaling law.

A new and significant mode of high performance optimised shear plasmas were developed during the year. Internal transport barriers were produced in this type of plasma. Under these conditions, H-mode levels of confinement were obtained during the L-mode phase of the discharge, and fusion performance was already comparable to that obtained in the best hot-ion H-modes.

JET is the largest and most powerful fusion experiment currently operating. It has the capacity to study reactor relevant problems and to provide further important information for the International Thermonuclear Experimental Reactor (ITER) (the collaboration between Euratom and the Governments of Japan, the Russian Federation and the USA). An extension of JET to the end of 1999 was officially approved by the Council of Ministers of the European Union in May 1996. In particular, the extension will: make essential contributions to the development and demonstration of a viable divertor concept for ITER; permit carrying out experiments using D-T plasmas in an ITER-like configuration, which will provide a firm basis for the D-T operation of ITER; and allow key ITER-relevant technology activities, such as the demonstration of remote handling and tritium handling.

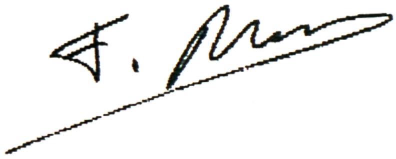
In May 1996, the Technology Centre of Finland (TEKES) formally acceded to JET, which will be a further welcome addition to the Undertaking. The Austrian Academy of Sciences has also applied for membership of JET. Procedures are now in train to have a change of JET membership among the German Associations, with FZK (Karlsruhe) to replace Forschungszentrum Julich GmbH.

During 1996, and in agreement with the appropriate Committee in the European Parliament (CERT), new procedures came into effect whereby certain information on the activities of the JET Council and the JET Scientific Council were published, thus improving the"transparency" of JETs management.

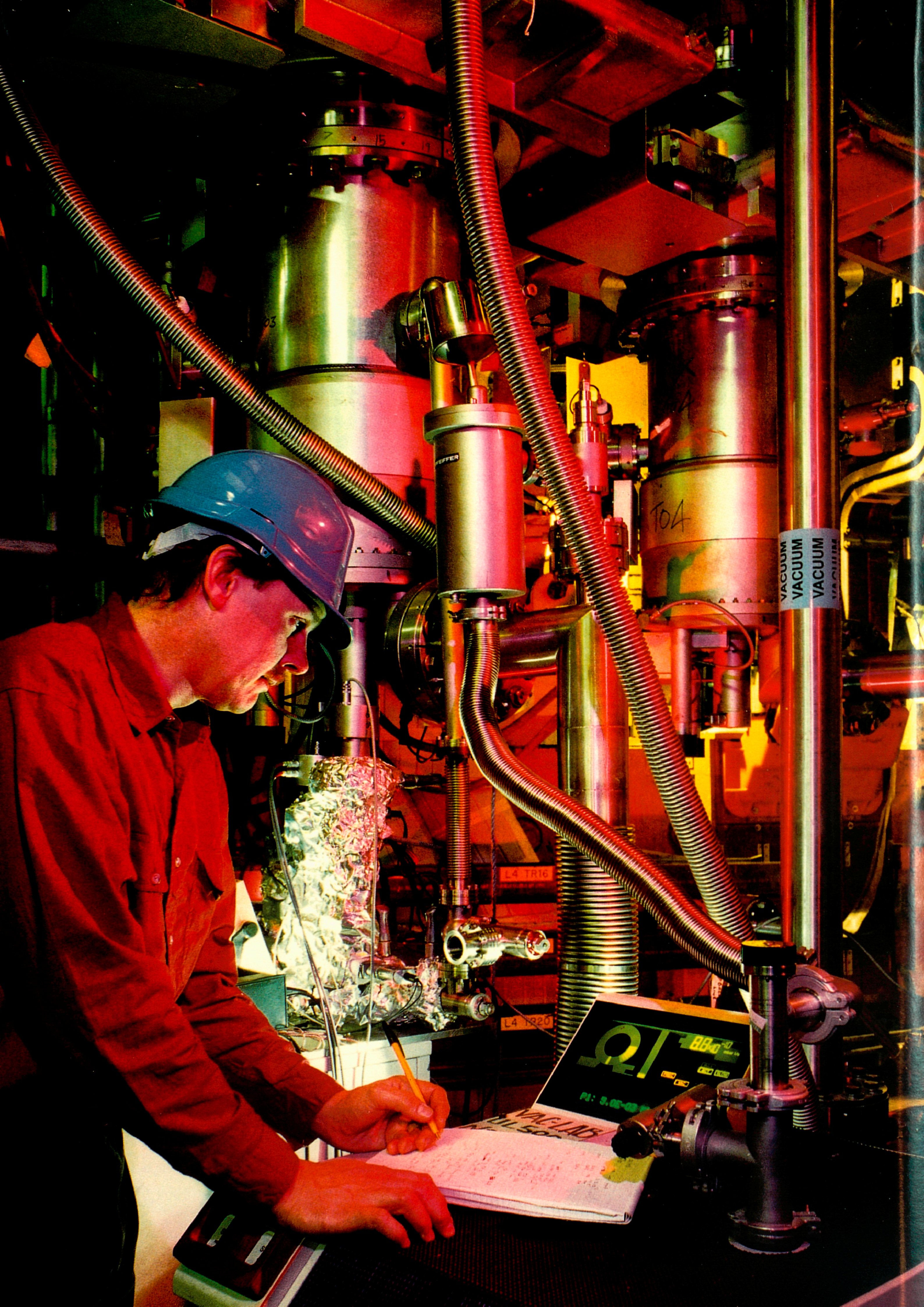
In December, Dr P Fasella retired from the JET Council having served as its Vice-Chairman and Chairman extending over a period which started in 1982. On this occasion, I would like to express the gratitude of all his colleagues for his important contributions over that period. In addition, Mr F Turvey retired as Chairman of the JET Executive Committee after serving for more than six years. Dr G Leman replaces him, as the new Chairman. Dr K Lackner was renominated Chairman of the JET Scientific Council.

On behalf of my colleagues on the JET Council, I would like to express our gratitude to the staff for their continued dedication to the Project. I thank the members of the JET Council for their unfailing support throughout the year; the members of the JET Scientific Council for their sound advice; and members of the JET Executive Committee for continuing to monitor the financial, contractual, and personnel aspects of the Project.

Despite tight budgetary constraints JET is continuing to advance the understanding of plasma physics and to provide fundamental results for ITER. The continuing dedication and innovation of JET staff provides confidence that the Project will meet the challenges ahead and help to foster fusion as a major source of energy for the future.



F. Troyon
Chairman of the JET Council
May 1997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Introduction, Summary and Background

Introduction

The Joint European Torus (JET) is the largest project in the coordinated fusion programme of the European Atomic Energy Community (EURATOM), whose long term objective is the joint creation of safe environmentally sound prototype fusion reactors.

The Statutes setting up the JET Project include a requirement for an Annual Report to be produced which:

> *'... shall show the current status of the Project, in particular with regard to timetables, cost, performance of the scientific programme and its position in the Euratom Fusion Programme and in the world-wide development of fusion research.'*

This Report is designed to meet this requirement. It provides an overview of the scientific, technical and administrative status of the JET programme, which is intended to be comprehensible to the average member of the public. Where appropriate, descriptive sections (in italics and boxed) are included to aid the reader's understanding of particular technical terms used throughout the Report.

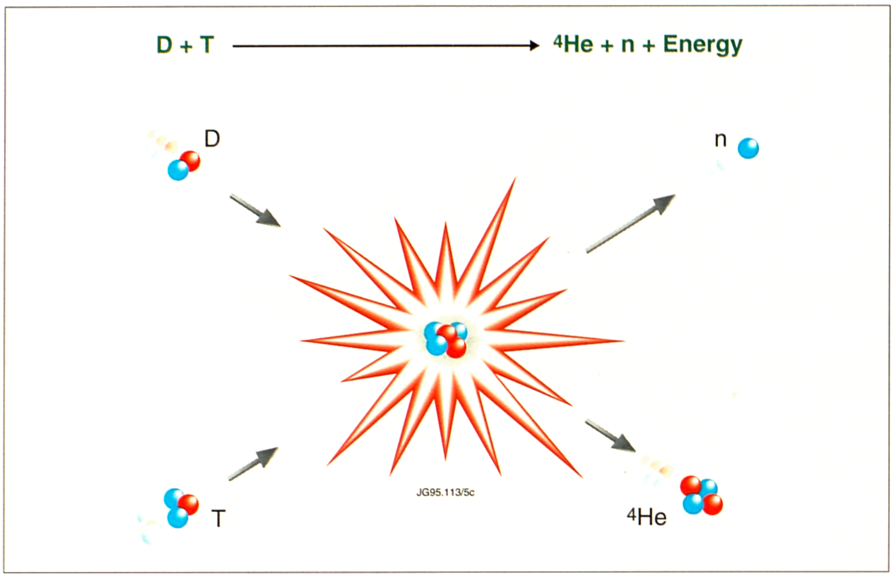
A more detailed and comprehensive description of the technical aspects of the JET Project can be found in the JET Progress Report.

Report Summary

The Report is essentially divided into two main parts:

- the scientific and technical programme of the Project;
- the administration and organization of the Project.

The first part of the Report includes a brief introduction, provides an overview of the planning of the Report and sets the background to the Project. This is followed by a description of JET and its experimental programme and explains its position in the overall Euratom and International Fusion Programmes. In addition,



Nuclear Fusion

Energy is released when the nuclei of light elements fuse or join together to form heavier ones. The easiest reaction to achieve is between the two heavy isotopes of hydrogen (deuterium and tritium).

Most of the energy released in this reaction is carried away by a high speed neutron. The remaining energy goes to the alpha-particle (helium nucleus, ^4He) which is also produced in the reaction. In a fusion reactor, a jacket or blanket around the reactor region would slow down the neutrons, converting their energy into heat. This heat could be extracted to raise steam for conventional electricity generation.

it relates and compares JET to other large fusion devices throughout the world and confirms its pre-eminent position in fusion research.

The following section reports the technical status of JET including: the completion of technical changes during the latest shutdown to install the next stage divertor configuration (Mark II); preparations for future tritium experiments (DTE1 and DTE2) and progress on systems for future operation. This is followed by a section on scientific achievements during 1996. It sets out progress towards reactor conditions and compares the performance between JET and other tokamaks. It shows the substantial achievements made by JET since the start of operations in 1983. The scientific part of this Report concludes with a description of the proposed future programme of JET until its planned conclusion.

The second part of the Report explains the organisation and management of the Project. It describes the administration of JET, in which it details the budget situation; contractual arrangements; and sets out staffing arrangements and complement.

Background

In the early 1970's, discussions were taking place within the European fusion research programme on a proposal to build a large tokamak fusion device to extend the plasma parameters closer to those required in a reactor. In 1973, an international design team started work in the UK, and by mid-1975, the team had completed its design for a very large tokamak device.

On 30th May 1978, the Council of Ministers of the European Communities decided to build the Joint European Torus (JET) as a Joint Undertaking of the European Fusion Programme. To implement the Project, the Joint Undertaking was originally established

Fuels

As deuterium is a common and readily separated component of water, there is a virtually inexhaustible supply in the oceans of the world. In contrast, tritium does not occur naturally in any significant quantities and must be manufactured. This can be achieved by using reactions that occur between neutrons formed in the fusion reactions and the light metal lithium.

Therefore, although the fusion reactions occurring in a reactor will be between deuterium and tritium, the consumables will be deuterium and lithium.

Fusion Reaction $D + T \rightarrow {}^4He + n$

Tritium Breeding Reactions $^6Li + n \rightarrow T + {}^4He$

$^7Li + n \rightarrow T + {}^4He + n$

There are sufficient reserves of lithium available to enable world electricity generation using fusion reactors, to be maintained at present levels, for several hundreds of years.

for a period of 12 years, beginning on 1st June 1978. The device would be built on a site adjacent to Culham Laboratory, the nuclear fusion research laboratory of the United Kingdom Atomic Energy Authority (UKAEA), and that the UKAEA would act as Host Organisation to the Project. Figure 1 shows an aerial view of the site of the JET Joint Undertaking at Culham in the United Kingdom.

The Members of the Joint Undertaking are Euratom, its Associated Partners (including Finland, who joined in 1996) in the framework of the Fusion Programme, including Switzerland, together with Greece and Luxembourg, who have no Contracts of Association with Euratom.

Eighty per cent of the expenditure of the Joint Undertaking is borne by Euratom. As the host organisation, UKAEA pays ten per cent, with the remainder shared between Members having Contracts of Association with Euratom in proportion to the Euratom financial participation in the total costs of the Associations.

The Project Team is formed mainly by personnel from the Associated Institutions, although some staff are assigned on a secondment basis from the Institutions and the Directorate General of the Commission responsible for Science Research and Development (DGXII).

In July 1988, the Council of Ministers agreed the prolongation of the JET Joint Undertaking to 31st December 1992. A further proposal to prolong JET to 31st December 1996 was approved by the Council of Ministers in December 1991. The extension was to allow JET to implement the new Pumped Divertor Phase of operation, the objective of which was to establish effective control of plasma impurities in operating conditions close to those of the Next Step. An extension of the JET programme to 1999 in support of the ITER divertor while satisfying the requirements of JET D-T operations was approved by the Council of Ministers in May 1996.

Conditions for Fusion

Fusion reactions can only take place if the nuclei are brought close to one another. However, all nuclei carry a positive charge and therefore repel each other. By heating the gaseous fuels to very high temperatures, sufficient energy can be given to the nuclei that the repulsive force can be overcome and they to fuse together. In the deuterium-tritium reaction, temperatures in excess of 100 million degrees Kelvin are required - several times hotter than the centre of the sun. Below 100 million degrees, the deuterium-tritium reaction rate falls off very rapidly: to one-tenth at 50 million degrees, and 20,000 times lower at 10 million degrees.

A reactor must obtain more energy from the fusion reactions than is put in to heat the fuels and run the system. Reactor power output depends on the square of the number (n_i) of nuclei per unit volume (density) and the volume of gas.

Power losses must also be kept to a minimum acceptable level by holding the hot gases in thermal isolation from their surroundings. The effectiveness of this isolation can be measured by the energy confinement time (τ_E) - the time taken for the system to cool down once all external forms of heating are switched off.

In a fusion reactor the values of temperature, density and energy confinement time must be such that their product ($n_i\tau_E T_i$), exceeds the figure of $5x10^{21}m^{-3}skeV$. Typical values for the parameters that must be attained simultaneously for a reactor are:

Central ion temperature, T_i
10-20keV
Central ion density, n_i
$2.5x10^{20}m^{-3}$
Energy confinement time, τ_E
1-2s

The temperature is expressed as the average energy of the nuclei (1keV is approximately equal to 10 million degrees K).

Objectives of JET

The original decision of the Council of Ministers in 1978 states that the JET Joint Undertaking's mandate is to:

'... construct, operate and exploit as part of the Euratom fusion programme and for the benefit of its participants in this programme, a large torus facility of tokamak-type and its auxiliary facilities in order to extend the parameter range applicable to controlled thermonuclear fusion experiments up to conditions close to those needed in a thermonuclear reactor.'

The principal objective of JET is to enable the essential requirements of a tokamak reactor to be defined. To implement this, it was necessary to create and study plasma in near-reactor conditions.

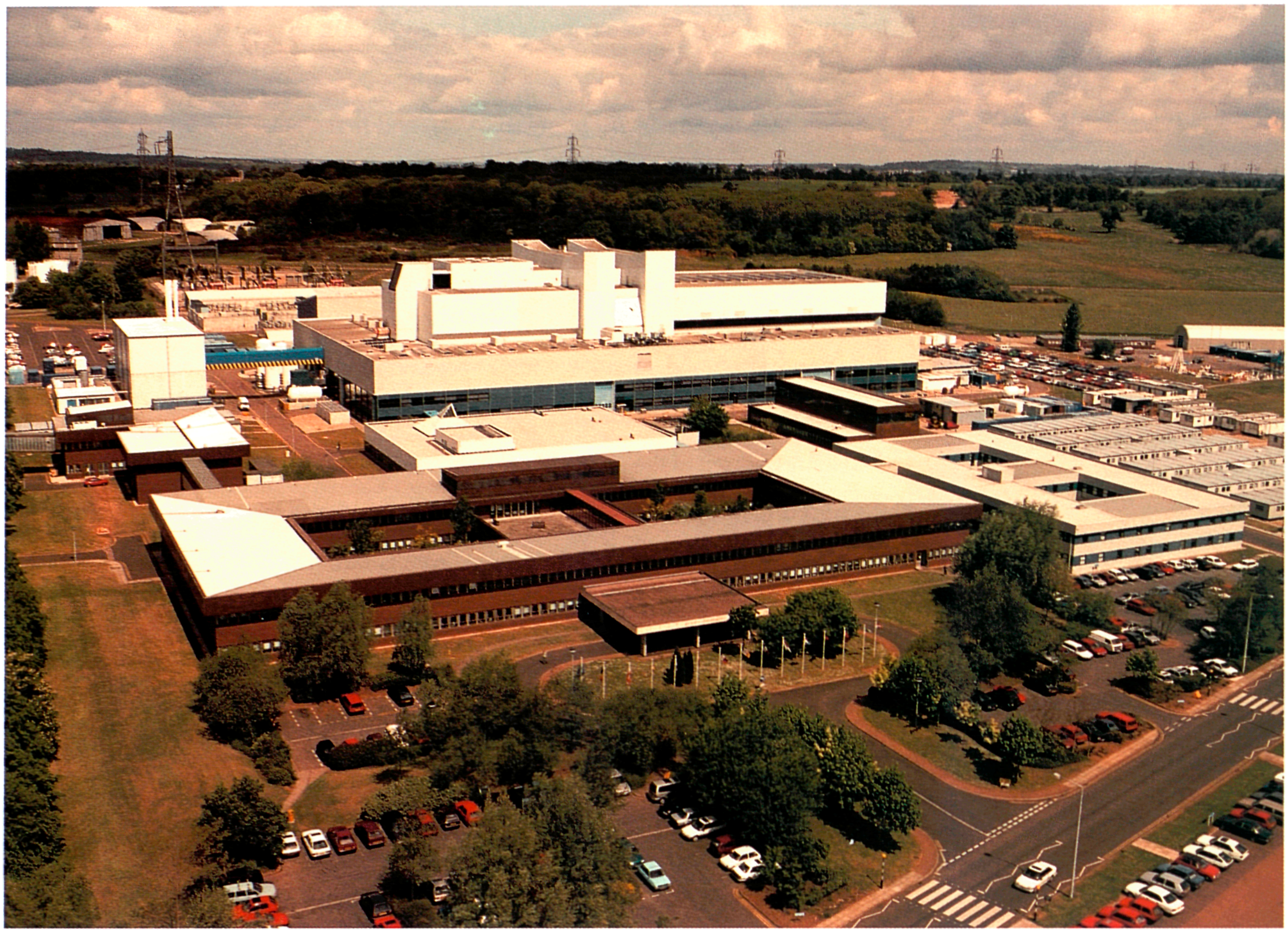
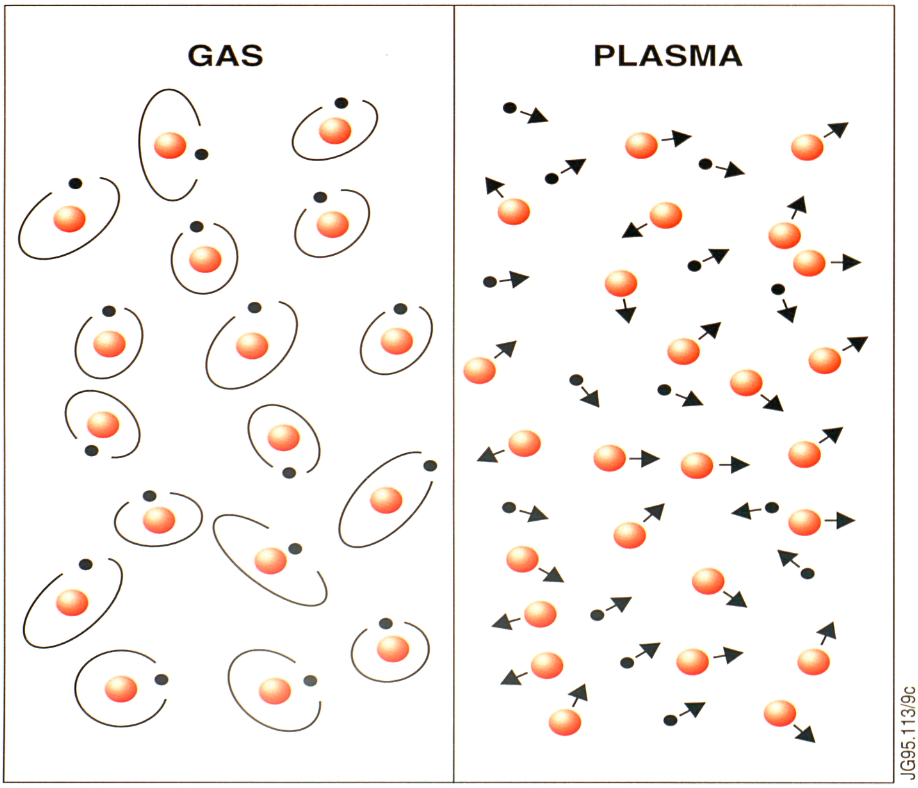


Fig.1: Aerial view of the JET Joint Undertaking, situated near Oxford in the United Kingdom



Plasma

As the temperature of the fuel is increased, the atoms in the gas become ionised, losing their electrons, which normally orbit around the nuclei. The mixture of positively charged ions and negatively charged electrons is very different from a normal gas and is given a special name - PLASMA.

The fact that a plasma is a mixture of charged particles means it can be controlled and influenced by magnetic fields. With a suitably shaped field, it should be possible to confine the plasma with a high enough density and a sufficiently long energy confinement time to obtain a net energy gain.

The configuration that has so far advanced furthest towards achieving reactor conditions and on which most data is available is the TOKAMAK, originally developed in the USSR.

Fusion Reactor

In a fusion reactor a lithium compound would be incorporated within a blanket surrounding the reactor core so that some neutrons can be utilised for manufacturing tritium. The tritium produced would then be extracted for use in the reactor.

The blanket would also provide the means of utilising the energy carried away from the reactions by the neutrons. As the neutrons are slowed down within the blanket, its temperature would rise thus enabling steam to be raised so that electricity could be generated in the conventional manner.

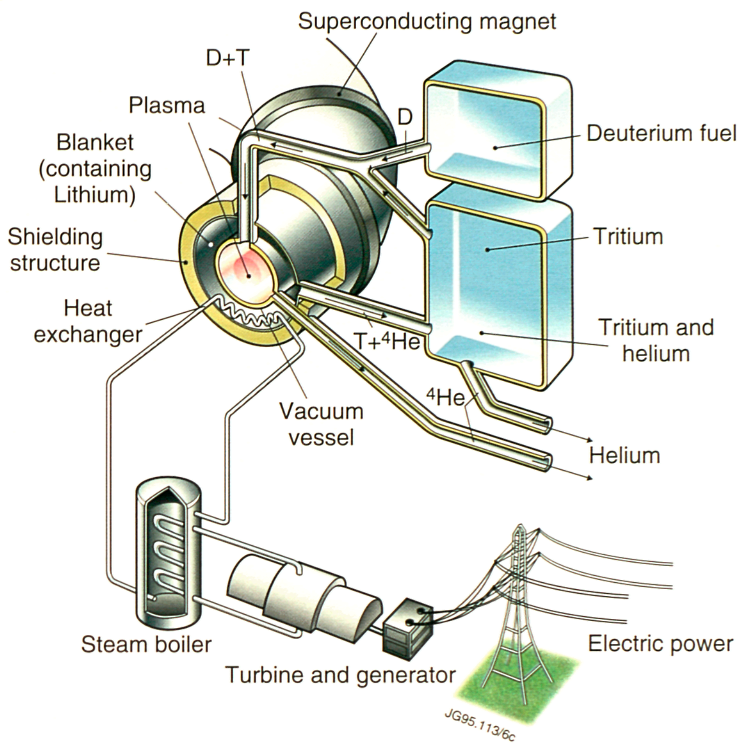
Ultimately, it is hoped that the conditions would be reached to enable a reactor to be built utilising the deuterium-deuterium reactions below:

$$D + D \rightarrow {}^{3}He + n$$

$$D + D \rightarrow T + p$$

In this case there would be no need to manufacture tritium and a virtually inexhaustible reserve of energy would become available.

Schematic of a Fusion Reactor



There are four main areas of work:

1. the study of scaling of plasma behaviour as parameters approach the reactor range;
2. the study of plasma-wall interaction in these conditions;
3. the study of plasma heating;
4. the study of alpha-particle production, confinement and consequent plasma heating.

In addition, JET is pioneering two key technologies required in fusion reactors: the use of tritium and remote handling techniques.

JET, Euratom and other Fusion Programmes

The Joint European Torus

JET uses the tokamak magnetic field configuration to maintain isolation between the hot plasma and the walls of the surrounding vacuum vessel. A diagram of the JET apparatus is shown in Fig.2 and the original main design parameters are presented in Table I.

The toroidal component of the magnetic field on JET is generated by 32 large D-shaped coils with copper windings, which are equally spaced around the machine. The

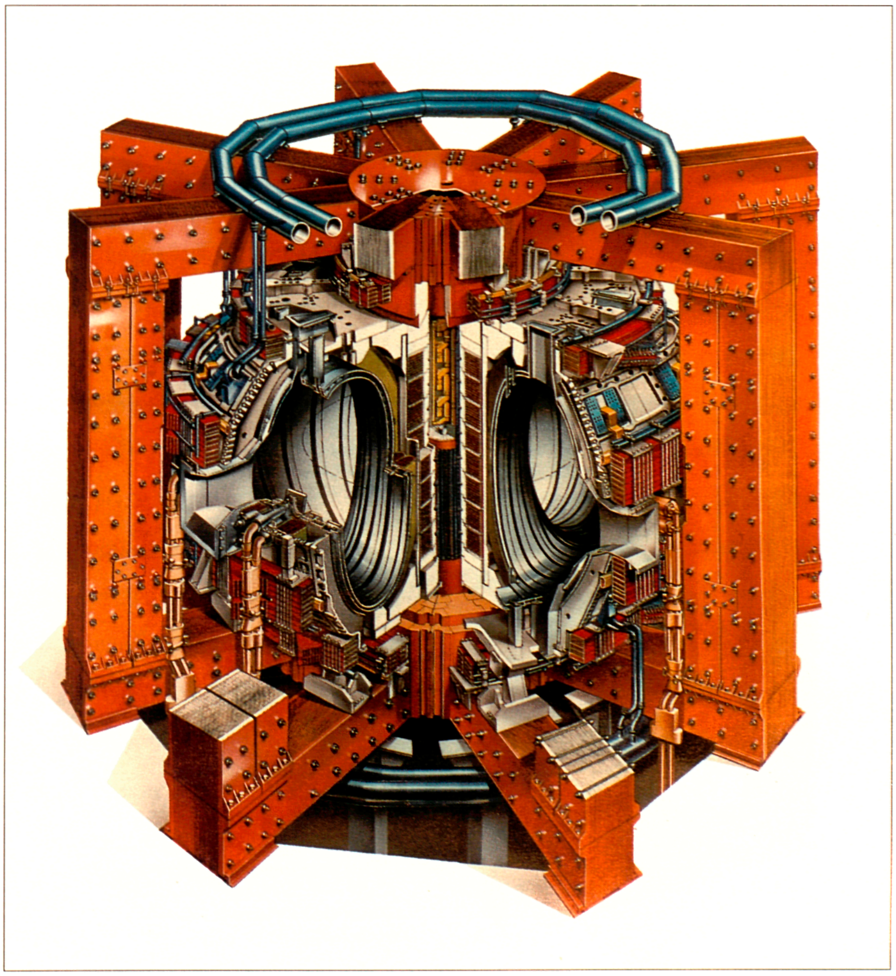


Fig.2: Technical illustration of the JET Apparatus

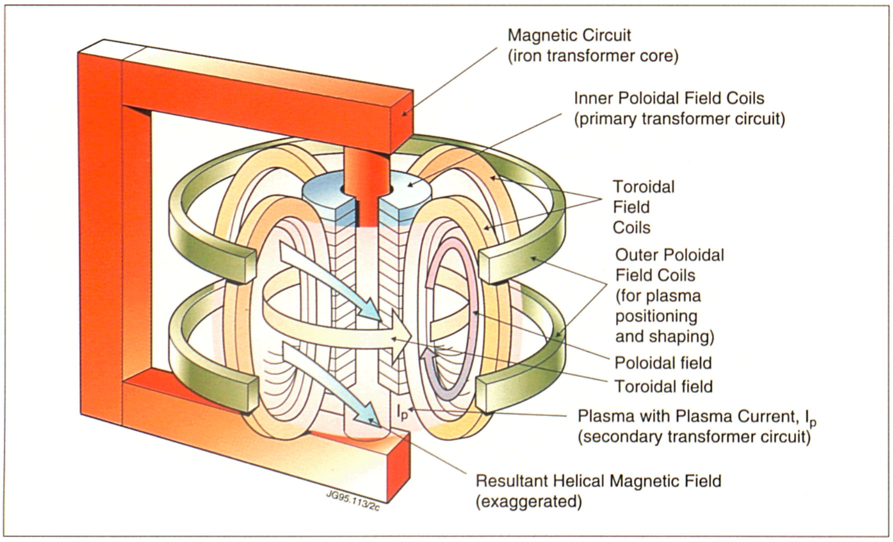
PARAMETER	SIZE
PLASMA MINOR RADIUS:	
HORIZONTAL	1.25m
VERTICAL	2.10m
PLASMA MAJOR RADIUS	2.96m
FLAT-TOP PULSE LENGTH	20s
WEIGHT OF THE IRON CORE	2800t
TOROIDAL FIELD COIL POWER (PEAK ON 13s RISE)	380MW
TOROIDAL MAGNETIC FIELD AT PLASMA CENTRE	3.45T
PLASMA CURRENT:	
CIRCULAR PLASMA	3.2MA
D-SHAPE PLASMA	4.8MA
VOLT-SECONDS TO DRIVE PLASMA CURRENT	34Vs
ADDITIONAL HEATING POWER	25MW

Table 2: Original JET parameters

primary winding (inner poloidal field coils) of the transformer, used to induce the plasma current which generates the poloidal component of the field, is situated at the centre of the machine. Coupling between the primary winding and the toroidal plasma, acting as the single turn secondary, is provided by the massive eight limbed transformer core. Around the outside of the machine, but within the confines of the transformer limbs, is the set of six field coils (outer poloidal field coils) used for positioning, shaping and stabilising the position of the plasma inside the vessel.

During operation large forces are produced due to interactions between the currents and magnetic fields. These forces are constrained by the mechanical structure which encloses the central components of the machine.

The use of transformer action for producing the large plasma current means that the JET machine operates in a pulsed mode. Pulses can be produced at a maximum rate of about one every twenty minutes, and each one can last for up to 60 seconds



Magnetic Field Configuration

The tokamak magnetic field configuration is built up from three components. The first of these is produced by a set of coils around the minor circumference. These coils produce the toroidal magnetic field around the major axis of the machine. The second component (poloidal field) is produced by a large current caused to flow through the plasma by transformer action. The combination of these produces a helical magnetic field which keeps the plasma away from the vessel walls. The final component is generated by a set of hoop coils, which is used to shape and stabilise the position of the plasma.

Impurities

Impurities released from interactions between the plasma and material surfaces can have major effects on plasma behaviour by causing:

(a) increased radiation losses;

(b) dilution of the number of ions available in the plasma between which fusion reactions can occur.

A measure of the overall impurity level is given by Z_{eff} which is defined as the ***average*** *charge carried by the nuclei in the plasma. A pure hydrogen plasma would have $Z_{eff}=1$ and any impurities in the plasma would cause this value to be increased. In JET, Z_{eff} is generally in the range from 1.2-3.*

Major energy losses can result from two radiation processes:

- *Bremsstrahlung Radiation - radiation is emitted when electrons are decelerated in the electric field of an ion. The amount of radiation emitted increases with Z_{eff}. Bremsstrahlung radiation imposes a fundamental limit to the minimum plasma temperature that must be attained in a fusion reactor;*
- *Line Radiation - heavy impurities will not be fully ionised even in the centre of the plasma and energy can therefore be lost through line radiation.*

Considerable effort is made to keep the level of impurities in the JET plasma to a minimum. The vacuum vessel is baked at 300°C to remove gas particles trapped on the vessel walls which might be released by plasma bombardment.

Interactions between the plasma and vacuum vessel walls would result in the release of heavy metal impurities. To reduce this possibility, the edge of the plasma is defined by upper and lower belt limiters. These are cooled structures circling the outboard torus wall with carbon or beryllium tiles attached. Carbon and beryllium have a relatively low electric charge on the nucleus.

in duration. The plasma is enclosed within the doughnut shaped vacuum vessel which has a major radius of 2.96m and a D-shaped cross-section of 4.2m by 2.5m. The amount of gas introduced into the vessel for an experimental pulse amounts to less than one tenth of a gramme.

The construction phase of the Project, from 1978 to 1983, was completed successfully within the scheduled period and within 8% of projected cost of 184.6 MioECU at January 1977 values. The first plasma pulse was achieved on 25 June 1983 with a plasma current of 17000A lasting for about one tenth of a second. This first phase of operation was carried out using only the large plasma current to heat the gas. In 1985, the first additional heating system, employing radio-frequency heating, came into operation and during 1991 reached 22MW of power into the plasma. The neutral beam heating system was brought into operation in 1986, and exceeded its design capability in 1988, with 21.6MW of power injected into the torus.

Experiments have been carried out mainly using hydrogen or deuterium plasmas, although during 1991, experiments were performed in helium-3 and helium-4 and a preliminary experiment was performed using 10% tritium in deuterium. In the final stages of the programme, it is planned to operate with deuterium-tritium plasmas so that abundant fusion reactions occur. The alpha-particles liberated from the reactions should produce significant heating of the plasma. During this phase, the machine structure will become radioactive to the extent that any repairs and maintenance would have to be carried out using remote handling systems.

The Community Fusion Programme

Objective, Strategy and Near-term Programme

The long-term objective of the programme, embracing all activities undertaken in Member States (plus Switzerland) in the field of controlled thermonuclear fusion by magnetic confinement, is "the joint creation of safe, environmentally sound prototype reactors, which should result in the construction of economically viable power stations, which will meet the needs of potential users..." (Council Decision 94/799/Euratom of 8 December 1994 adopting a specific programme of research and training in the field of controlled thermonuclear fusion, OJ No L 331, 21.12.94). The long timescale and the large personnel and financial effort needed to attain this objective call for a concentration of Community action on this objective; complete cohesion of the network of organizations associated in this Community action; and full exploitation of cooperation with major fusion programmes outside the Community.

Safety and environmental issues will play a central role in the realisation of large devices, which, after JET, are included in the strategy leading towards a prototype reactor. This strategy includes, in particular:

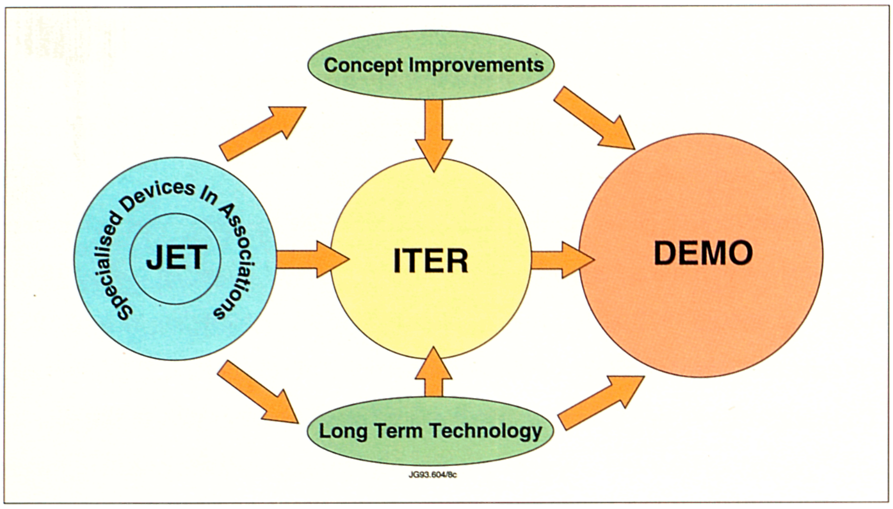


Fig.3: Interactions of European and International Activities

- an experimental reactor (Next Step), the overall objective of which is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes;
- a demonstration reactor (DEMO), capable of producing significant quantities of electricity.

For the period 1994-98, the priority objective is to establish the engineering design of the Next Step within the framework of the quadripartite cooperation on the Engineering Design Activities for the International Thermonuclear Experimental Reactor (ITER-EDA). Specialized studies are also needed to investigate possible improvements to concepts in plasma physics and plasma engineering, as well as to carry out long-term technology developments required for progressing towards exploitation of fusion as an energy source. The results of such studies will be of benefit both in the operation of ITER and, in the longer term, in the conceptual definition of DEMO.

Overall, the pursued strategy calls for simultaneous development of three major areas of activity (see Fig. 3), on which efforts are concentrated mainly by means of shared-cost actions:

- Next Step Activities: design proper, and R&D supporting design, construction and operation of the Next Step;
- Concept Improvements: R&D on plasma physics and engineering for the definition of DEMO and to help the finalization of the Next Step design;
- Long-term Technology: DEMO and reactor-oriented R&D on technology.

1996 Achievements

Concentration on the most successful toroidal magnetic confinement line, the tokamak, and on a few promising allied lines - while keeping a watching brief on inertial confinement fusion and on other approaches - continues to be fully justified by recent results. In the frame of the 1994-98 Fusion Programme, a large proportion of 1996 activities, including those on JET and within the Associated Laboratories, was in support of the Next Step.

Next Step Activities

The Next Step engineering design has progressed in the ITER-EDA, in the framework of Protocol 2 of the Quadripartite Agreement on Cooperation between Euratom, Japan, Russia and the USA. The overall programme objective of ITER is "to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes". ITER would accomplish this objective by "demonstrating controlled ignition and extended burn of deuterium-tritium plasmas, with steady-state as an ultimate goal, by demonstrating technologies essential to a reactor in an integrated system, and by performing integrated testing of the high-heat-flux and nuclear components required to utilize fusion energy for practical purposes". The ITER-EDA is conducted by the four ITER Parties under the auspices of the IAEA (International Atomic Energy Agency, Vienna) and carried out by a Joint Central Team (JCT) located in three internationally staffed joint work sites in San Diego (USA), Naka (Japan) and Garching (EU) and by four Home Teams.

In December 1996, the ITER Council, on the recommendation of its Technical Advisory Committee (TAC), submitted the ITER Detailed Design Report (DDR), Cost Review and Safety Analysis for consideration by the Parties. The ITER Council, noting the TAC recommendation that "the DDR offers a sound basis for proceeding to the Final Design", agreed that "the technical work of the EDA should continue on the basis of the DDR, taking account of the detailed technical findings and recommendations in the TAC Report". Furthermore, the ITER Council noted with appreciation that "essentially no change has occurred in the overall cost estimate presented in the Interim Design and Cost Review in 1995". At the request of the ITER Council, global framework scenarios towards siting, licensing and host support were developed. One approach was the concept of a project core of advanced fusion-relevant technologies whose cost should be equally borne by the ITER Parties. Informal explorations have started related to siting and host support to the project. Information is also being developed on the possible impacts of having ITER built in the European Union (at the October 1996 Research Council, Italy has shown its potential interest to host this project) or elsewhere (Japan, Canada, ...). Finally, an updated list of European firms and/or groupings of firms in the "15 Technologies" both specific to fusion and essential for the Next Step (in particular, the ITER-EDA) has been established by the Commission (with a validity of three years).

An extension of the JET Joint Undertaking (by three years to the end of 1999) was adopted (Council Decision 96/305/Euratom of 7 May 1996, OJ No. L 117, 14.5.1996) to allow the Project to make essential contributions to the development and demonstration of a viable divertor concept for ITER, and to carry out experiments using D-T plasmas in an ITER-like configuration, which will provide a firm basis for the D-T operation of ITER. By the same decision, the Technology Development Centre of Finland (TEKES) became a Member of the JET Joint Undertaking.

The NET (Next European Torus) Team continued to assist the Euratom Home Team (HT) Leader in the performance of his duties and responsibilities in the ITER framework.

Heating

Initial production and heating of the plasma is produced by the large electric current flowing in the plasma itself (ohmic heating) used to generate the poloidal magnetic field.

The heating effect of this current is reduced as the plasma gets hotter as the electrical resistance of the plasma decreases with increasing temperature. Therefore, it is necessary to provide additional means of heating if the temperatures needed for a reactor are to be reached.

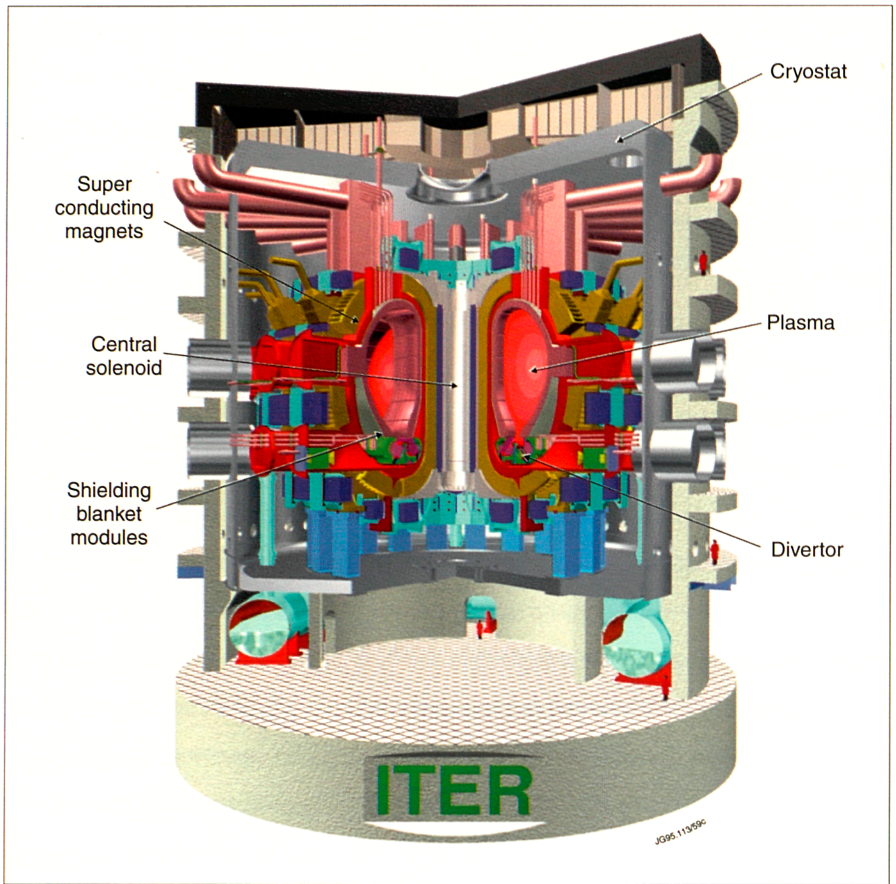
Two main additional heating methods are in general use:

(1) Neutral Beam Heating: In this method, a beam of charged hydrogen or deuterium ions is accelerated to high energies and directed towards the plasma. As charged particles cannot cross the magnetic field confining the plasma, the beam must be neutralised. The resulting neutral atoms cross the magnetic field and give up their energy through collisions to the plasma, thereby raising its temperature.

(2) Radio Frequency Heating: Energy can be absorbed by the plasma from high power radio-frequency waves. The frequency of operation is chosen to be close to that at which the ions or electrons orbit or gyrate in the magnetic field.

Concept Improvements

Research on concept improvements is essential for finalization of the design of the Next Step and, in the longer term, for the definition of DEMO. Concept improvements



Principal Parameters of ITER

Major Radius	*8.0m*
Minor Radius	*3.0m*
Elongation	*1.6*
Plasma Current	*24MA*
Toroidal Field	*5.7T*
Fusion Power	*1.5GW*
Burn Time	*1000s*

studies were carried out, in the Associated Laboratories, on the existing specialised devices (TORE SUPRA, ASDEX-Upgrade, TEXTOR, FTU, TCV, COMPASS, START, RTP, ISTTOK, W7-AS, RFX, EXTRAP-T2, etc), which explore the accessible parameter range and the possible modes of operation for different confinement concepts and configurations, and in the accompanying programmes of Member States where there is no Association. These devices also serve for fundamental fusion physics studies, for the development of diagnostics, for the preparation of collaboration on larger devices, for innovative studies and for the training of young professionals. These are the links which allow the incorporation of university research into theoretical, numerical or diagnostic activities.

On 31 May 1996, the Trilateral Euregio Cluster (TEC), joining fusion activities of three Associations (Euratom-Etat Belge, FOM and KFA), was ratified. The assessment of the upgrading of two Tokamaks was started (introduction of a dynamic ergodic divertor in TEXTOR at KFA-Julich; installation of a toroidal pump limiter and other plasma-facing components in TORE SUPRA at CEA-Cadarache). The TJ-2 Stellarator (CIEMAT-Madrid) became operational by the end of the year. Contracts of Association with Dublin City University and the Austrian Academy of Sciences were signed in August and November 1996, respectively.

Long-term Technology

The increased effort in long-term technology in the Associated Laboratories was pursued. For the European Blanket Programme (EBP, for which two options were chosen in 1995), a full work programme, up to the end of 1998, has been agreed and started. An update of the Safety and Environmental Assessment of Fusion Power (SEAFP 2) was undertaken in support of the long-term studies in the same field (SEAL, started in 1995). In the field of Materials for DEMO, in the frame of an Implementing Agreement of the International Energy Agency (IEA, Paris) - the conceptual design of an International Fusion Materials Irradiation Facility (IFMIF) was successfully completed. A Working Group on Socio-Economic Research on Fusion (SERF) was established, to provide input for a programme proposal.

Involvement of Industry in the Programme

European industry has been involved in the Fusion Programme for some long time. This has been undertaken by means of specific contracts for the supply of components, scientific equipment, materials and services for the construction and successive exploitation and upgrading of JET and the current generation of fusion facilities in the Associations and the JRC.

Measures have been implemented to strengthen the role of industry. This has the double aim of introducing industrial expertise into the realisation of the Next Step/ITER (in particular, at plant and systems engineering levels during its engineering design) and of ensuring that European industry will master all key technologies needed to build future fusion power plants (in particular, by encouraging more continuity in the industrial efforts in fusion specific R&D). Such measures are providing the foundations for involvement of industry in the possible construction of the Next Step/ITER. To meet related organisational and technical challenges, further steps will need to be taken to maximise the synergy between the Programme and relevant European industries.

Density Control

Increasing the density can be achieved by introducing additional gas into the vacuum vessel, by the injection of energetic neutral atoms (neutral beam heating) and by solid pellet injection.

Increasing the input power to the plasma through additional heating raises the electron density limit. However, problems can occur when this heating power is switched off, if the electron density is too high. To overcome this problem, the outer layer of the plasma is moved, prior to the switch-off point, so that it bears on the carbon tiles covering the inner wall. The tiles have been found, to provide a pumping mechanism for removing particles so that the density can be reduced below the critical limit.

Management of the Programme

All magnetic fusion research is integrated into one Community Fusion Programme which presents itself as a single body in its relations with other fusion programmes in the world. The European Commission, assisted by a Consultative Committee for the Fusion Programme (CCFP), composed of national representatives, is responsible for implementation of the Fusion Programme. The Programme operates principally through: Contracts of Association with Member States (plus Switzerland) or organisations within Member States, the JET Joint Undertaking, the NET Agreement (which takes account of the Euratom participation in the ITER-EDA), the JRC, Contracts of limited duration (in particular with organisations in Member States without Association) and industrial contracts. Through the Multipartite Agreement for "Promotion of Staff Mobility", the mobility of scientists and engineers was developed. In coordination with the "Human Capital and Mobility" programme, fellowships were awarded. The dissemination of knowledge and exploitation of results were performed through laboratory reports, publications in scientific journals, workshops and conferences. The itinerant fusion exhibition, run by the "Fusion

EXPO" consortium, was displayed in Austria, Denmark and Italy. On the occasion of the European Week for Scientific and Technological Culture, young post-graduates were selected to participate in the "Science Ambassadors" Project.

The Community financial participation amounts to about 25% of the running expenditure of the Associations, 45% of capital cost of projects having been awarded priority status by the CCFP, and 80% of JET expenditure. The overall expenditure on fusion research in Europe amounts to ~500 MioECU per annum, of which about 225 MioECU comes from the Community budget. About 2,000 professional scientists and engineers are currently engaged in fusion research in Europe. Following the accession of Austria, Finland and Sweden to the European Union, the envelope for fusion within the 1994-1998 Euratom framework programme was increased from 840 to 895 MioECU, including 49 MioECU for fusion activities at the JRC (Council Decision 96/253/Euratom of 4 March 1996, OJ No L 86, 4.4.1996).

Breakeven

This condition is reached when the power produced from fusion reactions is equal to that necessary for maintaining the required temperature and density in the plasma volume.

In agreement with the programme decision, a 1996 Fusion Evaluation Board was set up by the Commission to perform an external, independent assessment into the progress of fusion research in Europe during the last five years, and to examine the future prospects of nuclear fusion, and in comparison with other types of energy generation. In its report issued by the end of the year, the Board stated that "Fusion is one of the few energy sources which might make a significant contribution to satisfy the growing need for electricity from the middle of the 21st century onward. Taking into account intrinsic safety aspects, potential environmental advantages and the wide availability of fuel, it is important for Europe to have this option open". The Board confirmed the validity of the long-term R&D strategy recommended by previous panels. Starting the construction of ITER is recommended as the first priority of the Community Fusion Programme under the Fifth Framework Programme. ITER should, if possible, be built in Europe as "this would maintain Europe's position as world leader in fusion and would be of great advantage to European industry and laboratories".

Ignition

Ignition of a mixture of deuterium and tritium would be reached if the power produced by the alpha-particles (20% of the total thermo-nuclear power) released from the fusion reactions is sufficient to maintain the temperature of the plasma.

International Collaboration

The Community approach has led to an extensive collaboration between the fusion laboratories. For example, most Associations undertake work for other Associations. The Associations are partners in JET, NET and ITER, and carry out work for them through various contracts and agreements. The Programme has built across Europe a genuine scientific and technical community of large and small laboratories, readily able to welcome newcomers and directed towards a common goal. The leading position of the Community Fusion Programme has also made Europe an attractive partner for international collaboration. Apart from the most far-reaching collaboration illustrated by the ITER project, bilateral Framework Agreements have

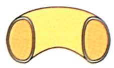
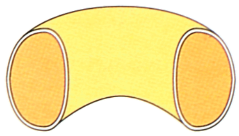
		TFTR	JET	ITER
				
MINOR RADIUS	a	0.85m	1.25m	3.0m
MAJOR RADIUS	R	2.5m	2.96m	8.0m
ELONGATION	κ	1.1	1.8	1.6
TOROIDAL FIELD	B	5.6T	3.45T	5.7T
INPUT POWER	P	48MW	36MW	30-200MW
FUSION FACTOR	Q_{DT}	0.3	1.1	30 - IGNITION
PLASMA CURRENT	I	3MA	7MA	24MA

Fig.4: Operating parameters of three large tokamak designs

been concluded (with the USA, Japan and Canada) or are to be concluded (with the Russian Federation, Ukraine and Kazakhstan). Finally, collaboration has progressed under the nine Implementing Agreements within the framework of the IEA.

Large International Tokamaks

The ITER Engineering Design Activity (EDA) is making good progress, and thus, achievements in tokamak research and, particularly, for the largest tokamaks (Fig. 4), have become even more relevant. Table 2 sets out an overview of the larger tokamaks worldwide, together with their main parameters and starting dates. Considerable progress has been made in these tokamaks, and these are highlighted below.

MACHINE	COUNTRY	MINOR RADIUS a(m)	ELONGATION κ	MAJOR RADIUS R(m)	PLASMA CURRENT I(MA)	TOROIDAL FIELD B(T)	INPUT POWER P(MW)	START DATE
JET	EC	1.00	1.8	2.96	7.0	3.5	42	1983
JT-60U	JAPAN	0.85	1.6	3.2	4.5	4.4	40	1991
TFTR	USA	0.85	1.0	2.50	2.7	5.6	48	1982
TORE-SUPRA	FRANCE	0.80	1.0	2.4	2.0	4.2	22	1988
T-15	CIS	0.70	1.0	2.4	2.0	4.0	-	1989
DIII-D	USA	0.67	2.5	1.67	3.0	2.1	27	1986
ASDEX-U	GERMANY	0.5	1.7	1.67	1.4	3.5	16	1991
FT-U	ITALY	0.31	1.0	0.92	1.2	7.5	-	1988

Table 2: Large Tokamaks operating around the World

In April 1996, the largest operating tokamak in the world, JET, restarted operation with a new divertor, which is more robust and capable of handling larger energy fluxes. The JET divertor programme is designed to investigate the effect of divertor geometry on the plasma performance in a series of progressively "more-closed" divertors. JET is now in the second stage, with the third stage planned after the D-T experiments in 1997. The experiments during 1996 were most successful and provide confidence for the forthcoming D-T operation (DTE1) in 1997.

Fusion Performance

During 1996, the US tokamak TFTR continued its D-T programme to further improve the fusion power produced. A fusion power of 10.7MW over a period of 1 second with a fusion efficiency, Q_{DT} of 0.27 was obtained. In addition to the so-called super-shot regime, other operating regimes were explored. In particular, high beta poloidal and negative central shear regimes with very high fusion performances were investigated. It was shown that in the relative quiescent phases in these plasmas, the alpha-particles behaved classically and no anomalous losses occurred. The effect of sawteeth and ELM's on alpha-particles were also studied.

The large Japanese tokamak device, JT60-U, has further improved on its previously good results. The highest fusion performance measured by the triple product $n_D.\tau_E.T_i$, now stands at $1.5x10^{21}m^{-3}$skeV in plasmas at 2.4MA with ion temperatures of 45keV. This produced an equivalent Q_{DT} of ~0.6. These results were obtained in the so-called high beta poloidal hot-ion H-mode regime, which in contrast to the normal hot-ion H-mode, has peaked density profiles (similar to those in the TFTR super-shot discharges). In contrast to the normal hot-ion H-mode, these JT-60U discharges saturated and levelled off over a period of ~0.5 seconds to a nearly constant level in the later stage of the pulse with a fusion triple product of $n_D.\tau_E.T_i$~$0.5x10^{21}m^{-3}$skeV.

Discharges with very high triangularity (δ=0.35) were maintained for 2.5 seconds at a triple product of $n_D.\tau_E.T_i$~$0.3x10^{21}m^{-3}$skeV and high plasma pressures β_N~2.5. Negative central shear regimes were produced with highly improved core confinement and showed very promising results with a Q_{DT} equivalent of ~0.83.

A summary of the fusion triple products obtained in the largest tokamaks is shown in Table 3.

Disruptions

There is a maximum value of density which can be contained with a given plasma current. If this value is exceeded a disruption occurs when the plasma confinement is suddenly destroyed and the plasma current falls to zero in a short period of time. Under these conditions high mechanical and thermal stresses are produced on the machine structure. Disruptions are thought to be caused by certain instabilities developing on specific magnetic surfaces.

Performance Limitations

No major effect on the transport processes in large tokamaks has been observed by instabilities related to fast particles and, in particular, the energetic alpha-particles, even at the high fusion power levels in TFTR. However, the highest performance

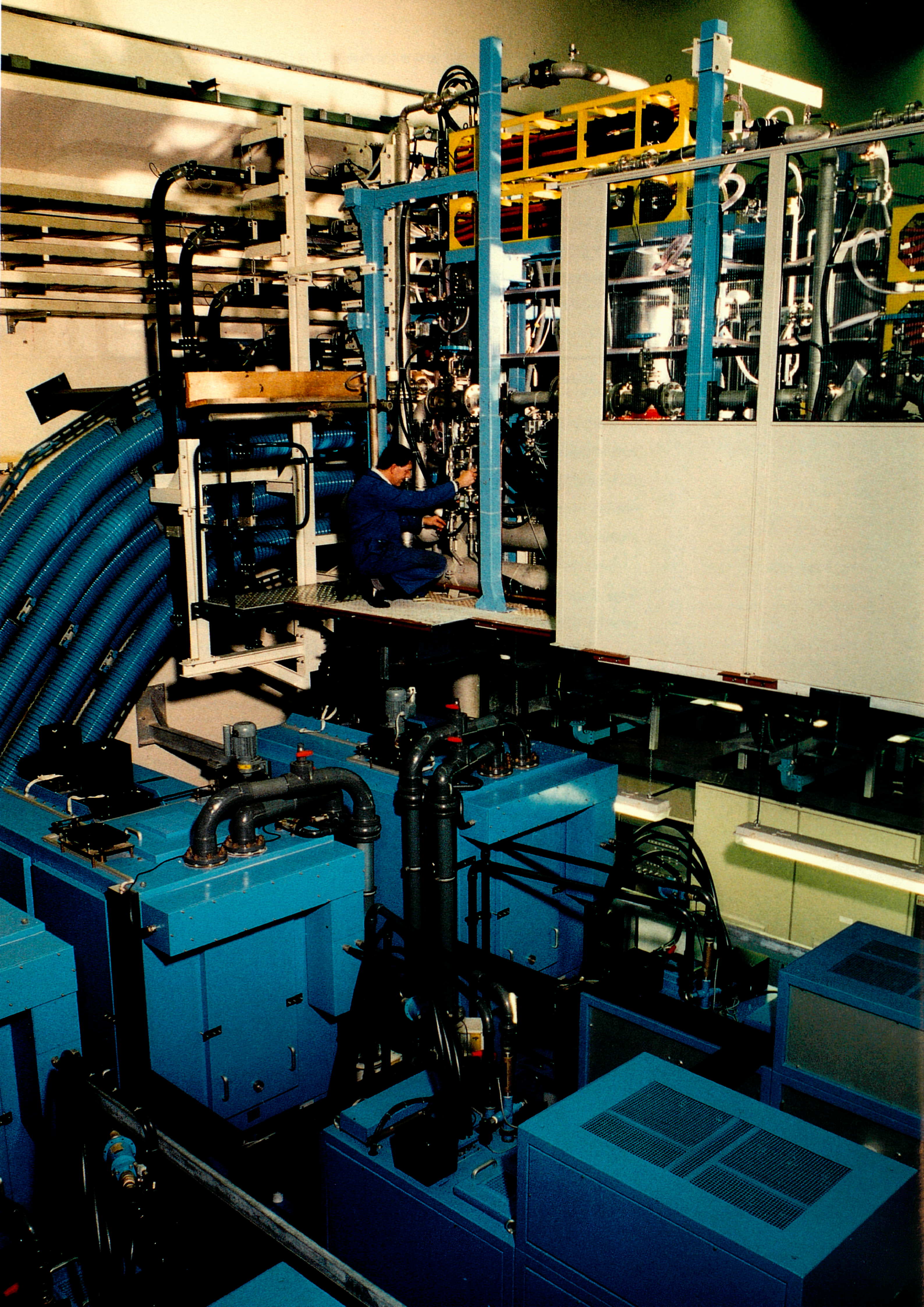
MACHINE	JET	JT-60U	TFTR	DIII-D
ELECTRON TEMPERATURE				
T_e(keV)	11	11	12	6
ION TEMPERATURE				
T_i (keV)	18	45	43	20
DURATION (s)	1.5	0.75	0.34	0.4
FUSION PRODUCT				
$n_iT_i\tau_E$ ($X10^{20}m^{-3}keVs$)	10	15.3	9.6	6.2

Table 3: Fusion Products in Large Tokamaks

discharges in the present machines are occurring over a limited period of time. Only when frequent MHD activity occurs, such as regular ELM activity, can a quasi-steady state be obtained. So, except for the high beta poloidal H-mode in JT60-U all other hot-ion H-mode discharges make a transition to a lower performance regime after a time of ~1 second.

In cases where the instabilities are related to steep edge pressure gradients, large Edge Localised Modes (so-called ELMs) occur, which usually lead to a permanent change in confinement. Real giant ELMs seem to be linked to instabilities caused by pressure and current densities at the plasma edge. Therefore, this suggests that careful control of the pressure profile and the edge current density is required to maintain the high performance phase.

The highly improved core confinement in the reversed shear or the optimised shear discharges seems to be linked to an absence of core MHD activity. Normally, there is an evolution of the current density profile and in the end the discharge favourable properties are curtailed. However, it is interesting that JT60-U has managed to sustain and control the reversed shear configuration by LHCD for a few seconds.



Technical Status of JET

Introduction

At the start of 1996, JET entered the ITER-EDA Support Phase of its International Thermonuclear Experimental Reactor (ITER) Support Programme. JET had already completed its Pumped Divertor Characterisation Phase by mid-1995. The objective had been to establish reliable methods of plasma purity control and plasma exhaust in operational conditions relevant for the Next Step tokamak. For this purpose, a pumped divertor which allowed tests of various configurations had been installed. This campaign had addressed the central problems of the ITER divertor: efficient dissipation of exhausted power; control of particle fluxes; and effective impurity screening.

JET started 1996 in shutdown for the installation of the Mark II divertor support structure. This will be the basis for all future divertor work at JET and is the key to the JET programme to 1999. In addition, the "more-closed" Mark IIA divertor target assembly was installed during the shutdown. Work was also undertaken on various systems in preparation for the next period of D-T operation (DTE-1), scheduled for Summer 1997, and for the Remote Tile Exchange shutdown after DTE-1.

The shutdown was completed on schedule at the end of March 1996 and was followed by pumpdown, leak testing and bake out, which were the quickest and most effective after a major shutdown. This reflected the quality of the in-vessel and ex-vessel methods and the experience gained.

The 1996 experimental campaign then concentrated on specific ITER-relevant issues related to the "more-closed" Mark IIA divertor and, due to their importance for predicting ITER's ignition margin and fusion power output, the scaling of the H-mode threshold power and the energy confinement. In addition, preparation of high performance scenarios for DTE1 was a high priority of the campaign.

A five week shutdown commenced at the end of September to plug divertor bypass leaks and to clad the inner wall of the vacuum vessel with graphite tiles. The experimental programme recommenced in November with the aim of optimising

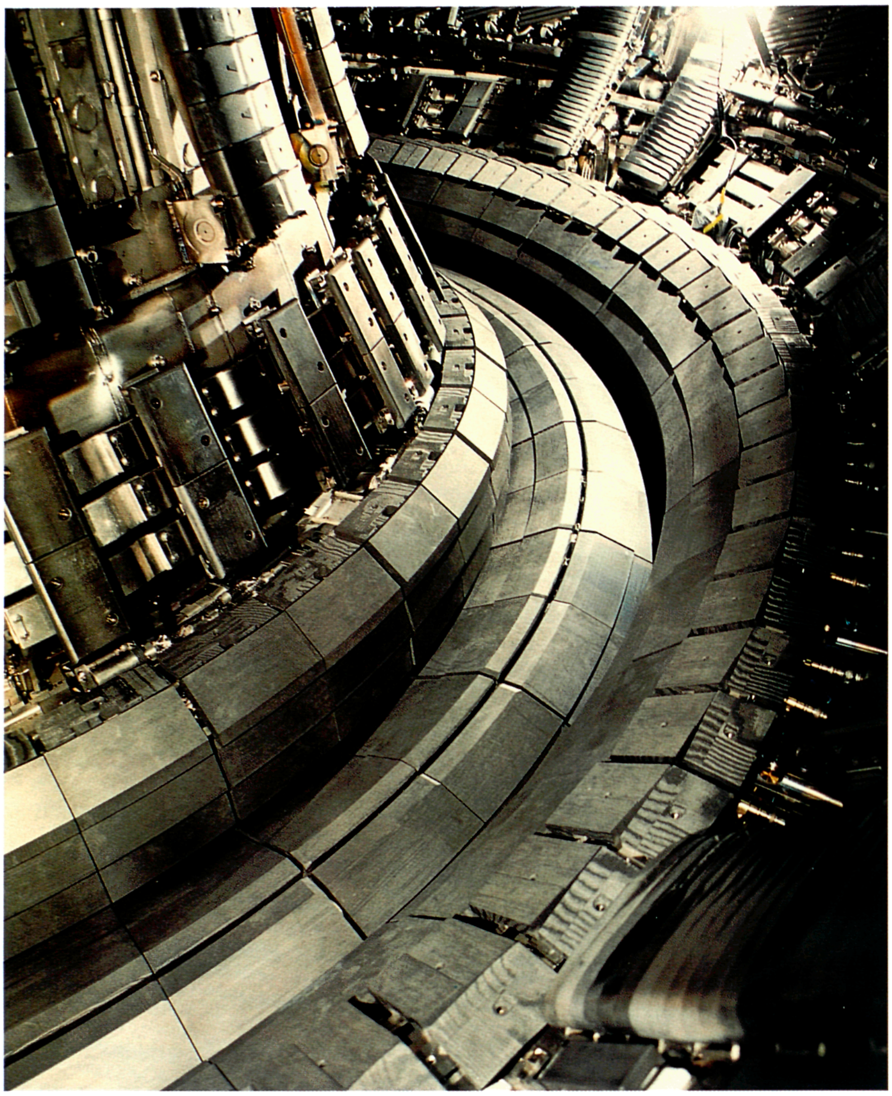


Fig.5: The installed Mark IIA divertor

performance in preparation for DTE-1 but was interrupted during the second half of December due to a water leak in the Octant No. 8 neutral beam injection box. This was repaired ready for operations to be restarted in early January 1997.

Preparations were also continuing for the next period of D-T operation (DTE-1), scheduled for Summer 1997. Work was also continuing on the procurement of the ITER specific Mark II Gas-box divertor target assembly, due to be installed by remote handling in 1997.

The following sections detail notable technical achievements during 1996.

Technical Achievements

First Wall Activities

Installation of the Mark II Divertor

The Mark II divertor was conceived to provide a "more-closed" configuration, leading to enhanced particle and impurity retention in the divertor chamber. It was designed to minimise modifications required to install different divertor configurations at later stages (such as Mark IIGB). The shutdown for installation had already started in June 1995 and continued in early 1996.

The Mark II design consists of a new inconel continuous water-cooled toroidal tray, which acts as support structure on top of the divertor coils. The tray is formed from three concentric rings, consisting of a base-plate, and an inner and

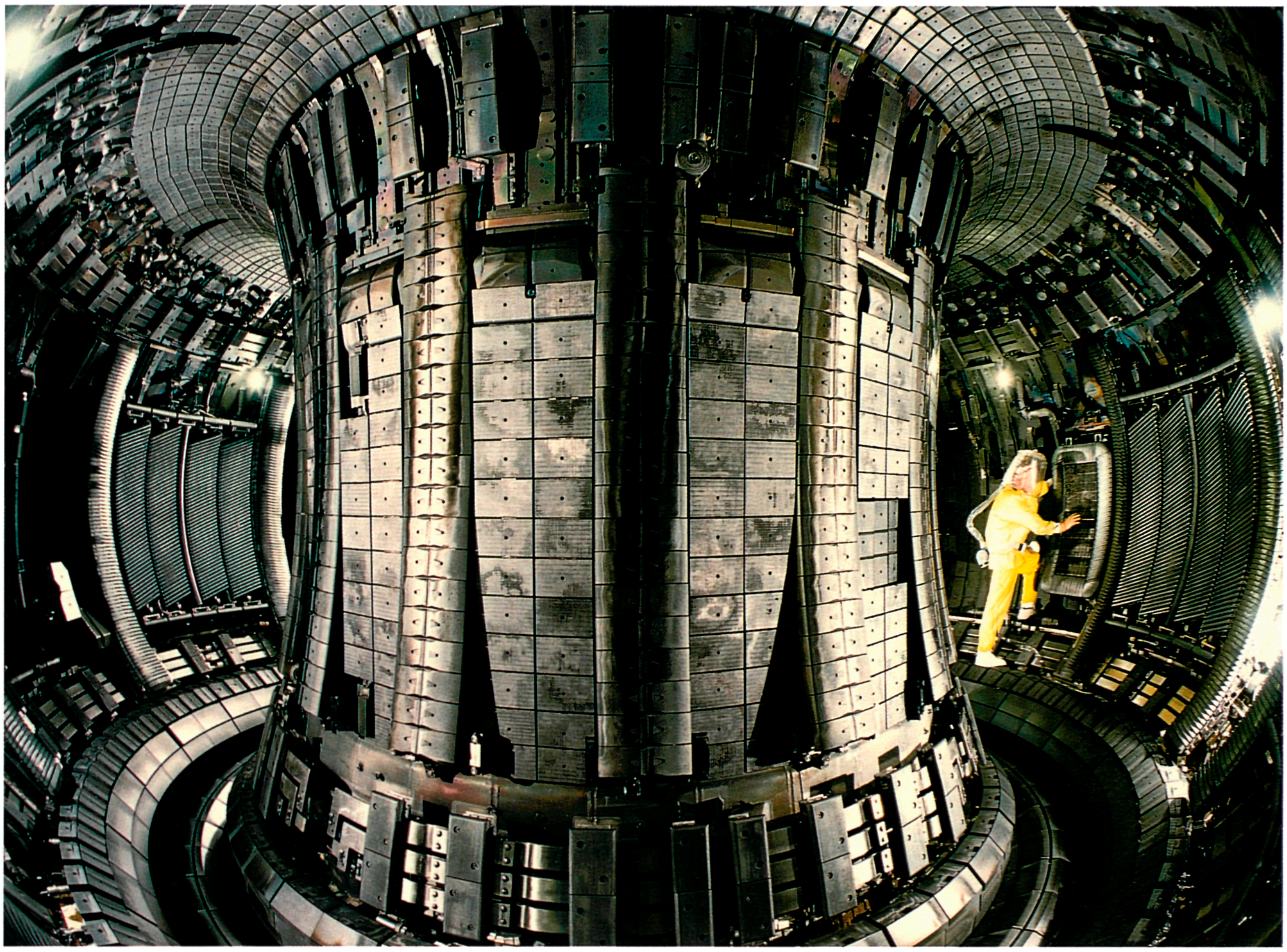


Fig.6: The new inner wall of JET showing the installed CFC cladding

an outer ring. The structure was made up of 24 modules, consisting of a honeycomb with vacuum and water retaining walls, manufactured with stringent specifications for vacuum tightness, mechanical properties, dimensional stability and corrosion resistance. On top of this structure, tile carriers and CFC tiles were installed to match the Mark II divertor configuration and could be subsequently replaced with different divertor configurations by means of remote handling. The restricted space and the hostile environment (radiation and beryllium contamination) effected design, requirements, and assembly procedures.

Surveys of the installed Mark IIA divertor tile carriers showed that after installation the gap between the tiles and the tile-to-tile steps were all well within the tight design parameters. The Mark II Divertor Installation Shutdown was completed by the end of March as planned. The divertor installed in the vessel is shown in Fig.5.

Bypass Leakage Reduction

At the end of September, an intervention was undertaken to install a system to prevent the divertor gas bypass leakage. The control of neutral gas leakage out of the divertor around the coils had relied upon thin metal plates with labyrinth gaps between them. It was found that additional preventive measures were required. A number of materials were tested for compatibility with high vacuum conditions up to 350°C. Obvious candidates such as glass fibre, carbon fibre and ceramic cloth were rejected on grounds of fibre shedding, electrical conductivity and water retention, respectively. Trials with polymers showed that Aramid cloth had the correct properties of vacuum compatibility, ease of handling, radiation resistance and low tritium uptake.

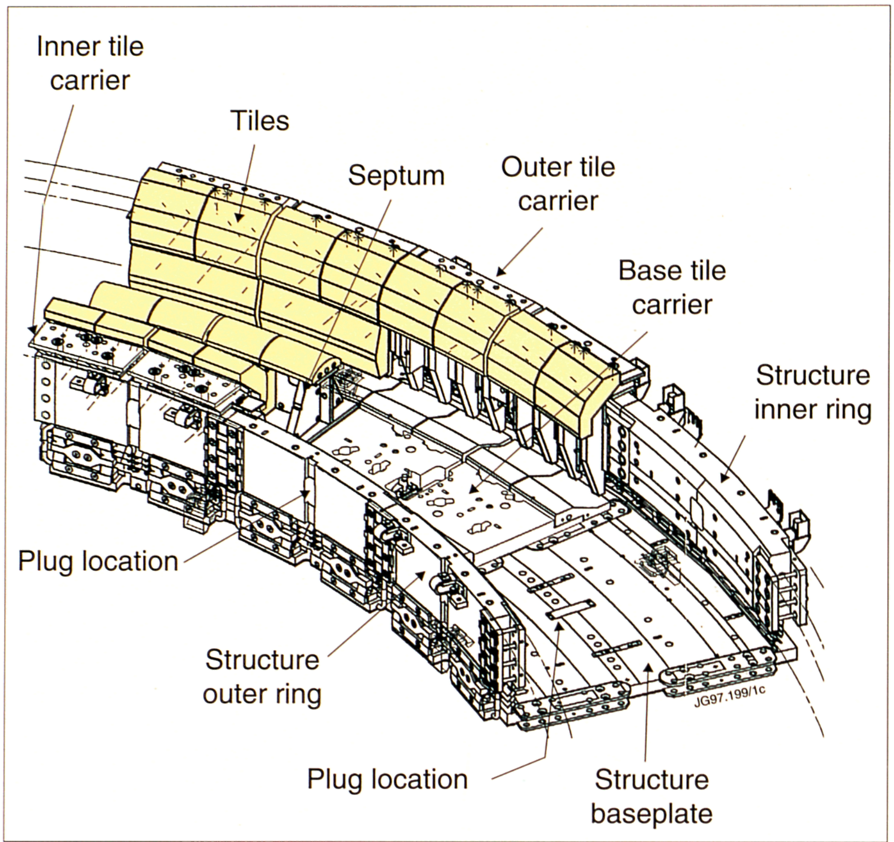


Fig.7: Model of the Mark II Gas-box Divertor

The gaps to be closed were those between the Divertor Coils Nos. 1 and 4 and the vessel wall, between Coil No. 1 and the divertor structure inner ring, and above the cryopump. Seals were made from two layers of folded Aramid cloth, sewn with Aramid thread, to form rectangular pads with rows of pockets along the edges. These pockets were shaped to give the cloth seal a U-form. This shape allowed it to be sprung into the relevant gap. Other gaps, such as those above the cryopump were closed either with polymide sheet clipped in place or flat Aramid seals laid on top of the existing metal gas shields.

During this intervention, the inner wall of the machine was clad with CFC tiles. The design of the cladding system consisted of beams in Inconel 600 to support the tiles. These beams were attached to the inner wall restraint rings. The cladding of the inner wall with CFC tiles was successfully completed and no major modifications were required to either the beams or the complex tooling required to install them and the individual supports. This was due to the detailed design and extensive trials and operator training performed in the In-Vessel Training Facility prior to installation. The inner wall with the new CFC cladding is shown in Fig.6.

Mark II Gas-Box Divertor

The Mark II Gas-box divertor tile carriers will be installed in the Mark II support structure during the 1997 remote installation shutdown. The novel feature of this divertor is the first use of CFC material for structural purposes in JET. The primary reason for the choice of CFC material is the relatively high heat flux ($\leq 2MWm^{-2}$) falling onto some structural components from the radiating gas target plasma (Fig.7). 1996 saw completion of the detailed design of this divertor and the beginning of manufacture of the tile carriers from CFC material. Manufacture of the CFC target tiles was competed.

Production of the series inner carriers started in November and will be followed by the septum, base and outer carriers. A test septum was assembled with different bolting systems to study their behaviour under cyclic load in a test

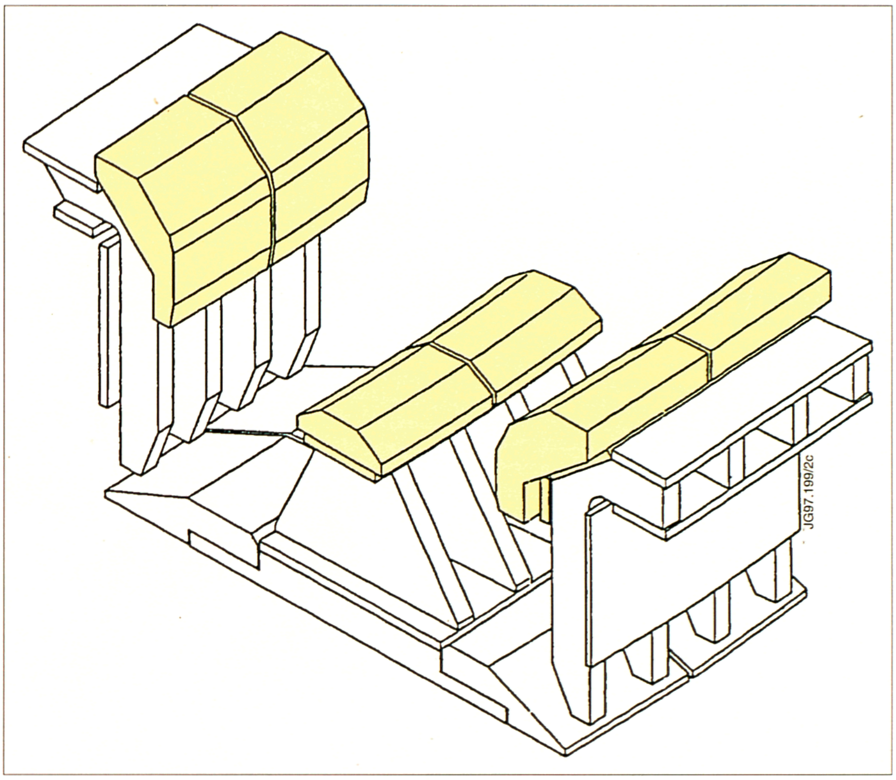


Fig.8: Mark II Gas-box divertor showing its make-up with toroidally discrete radially-oriented plates with a toroidally continuous top-tile

laboratory. This proved the effectiveness of the design (Fig.8). Detailed mechanical stress calculations including 3D finite element calculations were performed which predict adequate reserve factors for the structural CFC components.

High heat fluxes are expected to the various tiles of the gas box configuration that are not structural parts. Computations show that for a wide range of plasma parameters fluxes of up to 18MWm^{-2} are expected for non-radiating divertor plasma in the gas-box. Even for 10MW/leg total conducted power, the gas-box divertor will allow 3-6s of operation before the surface temperature reaches intolerable levels.

Remote Handling

Since the Mark II divertor will become active during its use with tritium plasmas, it has incorporated an important feature in its design - it has been engineered to allow replacement of the divertor target structure by full remote handling techniques. To validate the capability of this approach, about a quarter of the Mark II divertor tile carriers were installed in early 1996 by remote handling using the articulated boom and MASCOT servomanipulator. These carriers were installed following a detailed procedure previously tested and proven on the In-Vessel Training Facility (IVTF). An additional six carriers were installed at Octant No. 8, where the Boom was fully extended and where preparatory IVTF validations were not possible. In all locations, the tile carriers were successfully and safety installed within the time allotted (Fig.9).

In addition to the installation work, some time was taken to calibrate the general Boom teach files which will be used to position the Boom at all 48 tile carrier installations in 1997 and to confirm the effectiveness of the new Remote Handling In-Vessel Viewing System, which will be fundamental to all remote operations.

A full scale mock-up testing programme has been embarked upon to prepare the equipment and operators for the fully remote exchange of Mark II tile carriers. The programme includes the testing and proving of the task feasibility both under normal operating conditions and under failure case conditions. This mock-up programme, executed in the In-Vessel Training Facility as well as in the actual JET vessel, has been a major part of the remote handling work.

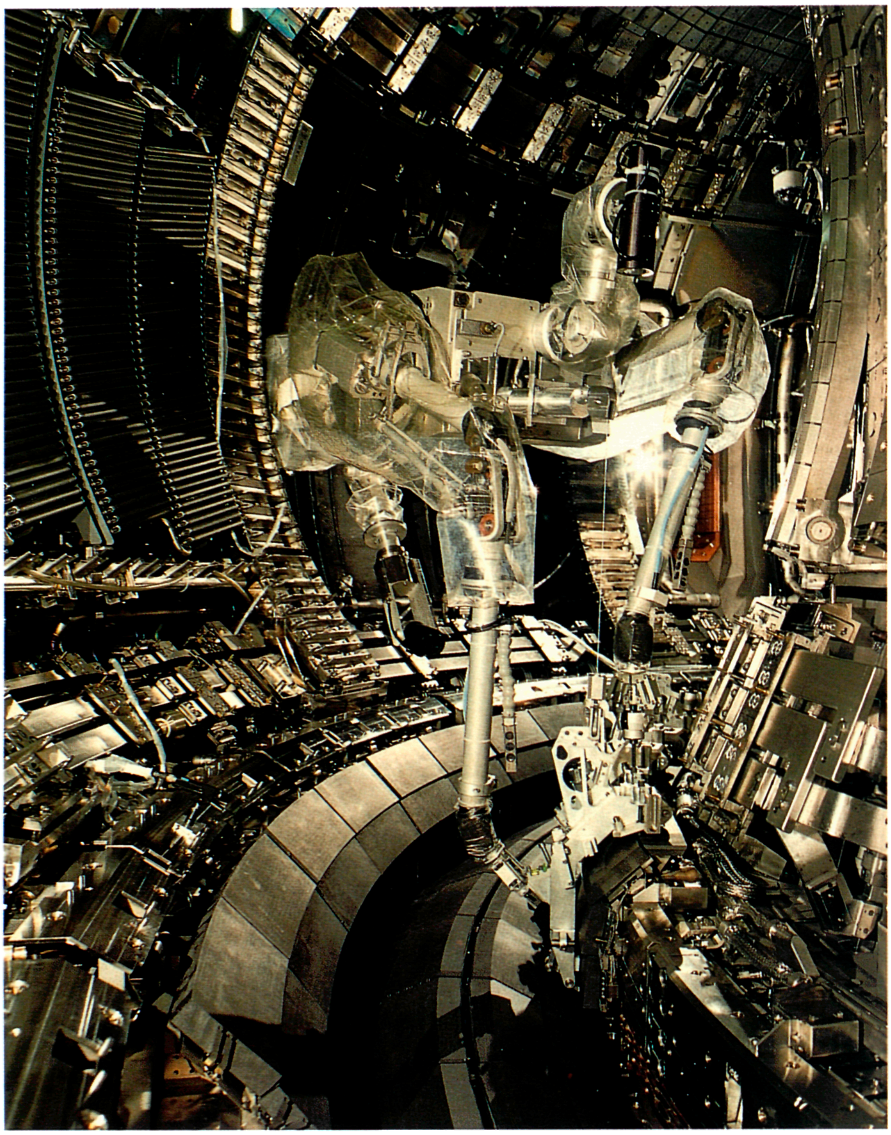


Fig.9: Remote Handling of Mark II Tile Carriers inside the torus during 1996

The Articulated Boom was utilised extensively in 1996 for remote handling trials. In August 1996, the system was taken out of operation to undergo upgrading and modification. The upgrading work has comprised modifications to many sub-systems resulting from 100 hour trial recommendations, experience from the mock-up operational programme, results of the failure recovery analysis and results of operational analysis. The major modifications include a new Boom section with improved range of movement, a new Boom Control System and incorporation of many features to facilitate Boom recovery after potential worst case failures.

The Tile carrier Transfer Facility comprising a short articulated Boom with a special end-effector, a pair of servo controlled storage trolleys and a contamination control enclosure surrounding the hardware has been installed during the 1996 shutdown.

Plasma Control

Due to enhanced asymmetry of the plasma in the divertor configuration and to the strong coupling with the divertor coils, greater demands have been made on machine control and protection. Disruptive instabilities frequently lead to loss of vertical position and, consequently, to larger vertical plasma displacements. The associated vertical force acting on the

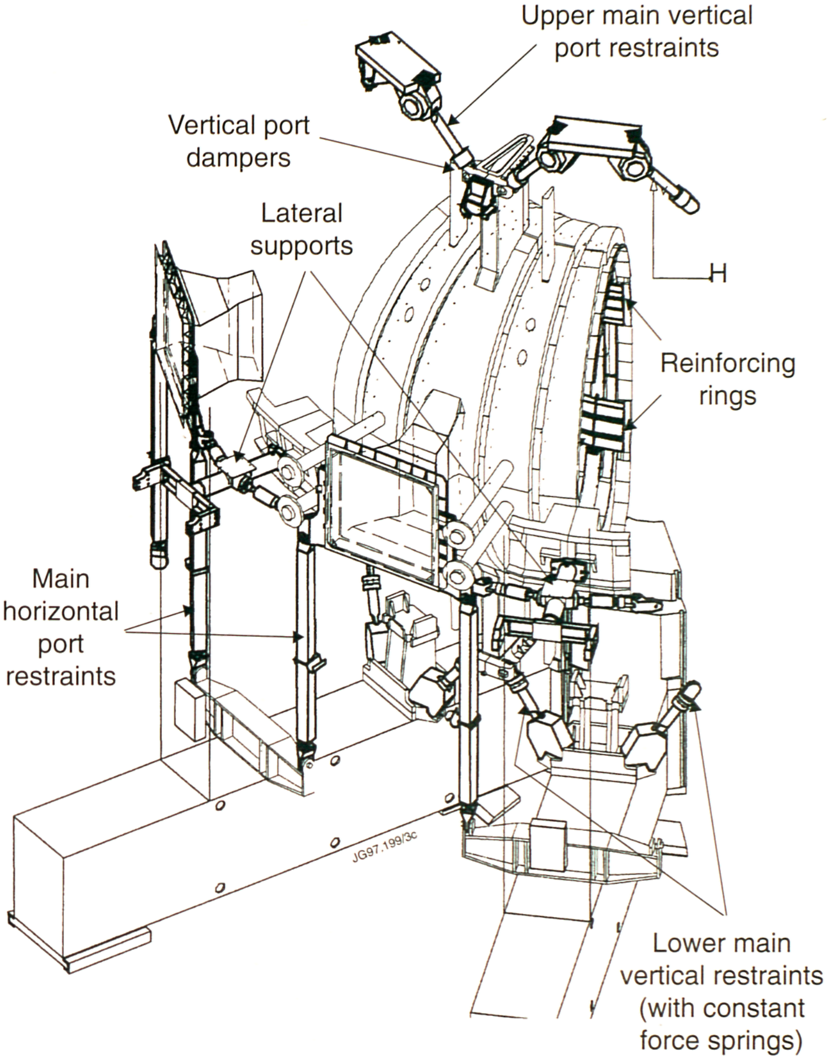


Fig.10: Restraints connected to the main horizontal and vertical ports of the vacuum vessel

vessel is large at high plasma current and when larger shaping currents are applied, such as divertor configurations. The vertical instability can produce potentially dangerous forces on in-vessel elements, such as protection tiles.

Since divertor (elongated) plasmas are more vertically unstable and require plasma-wall gap control, a new Plasma Position and Current control (PPCC) was introduced. The system was designed with 'intelligent' software to control plasma-wall gaps and poloidal coil currents. The new Plasma Control System (PPCC), played a key role in the success of the Mark I campaign. Its accuracy and flexibility in controlling plasma discharges have been further enhanced to better meet the requirements of operation with Mark II, by redesigning both the shape controller and the vertical stabilisation system, including both hardware and software. The updated shape controller showed better control of the poloidal flywheel generator, leading to a greater accuracy in plasma current control. The number of plasma-wall distances (gaps) to be controlled was increased, since this type of control is preferred as plasma shape and position do not change during the experiment, unlike other plasma parameters. The vertical stabilisation system upgrading was dictated by the necessity of attaining more information to study plasma behaviour during fast events, such as ELMs and by the decision to explore the possibility of using a soft X-ray diagnostic to control plasma vertical speed. The Mark II support structure is a continuous conducting toroidal tray, and induced currents would not allow the magnetic field null formation for breakdown. Therefore, this system now has the capability of generating a current proportional to the current induced in this structure, re-establishing the magnetic field null at the centre of the vacuum vessel.

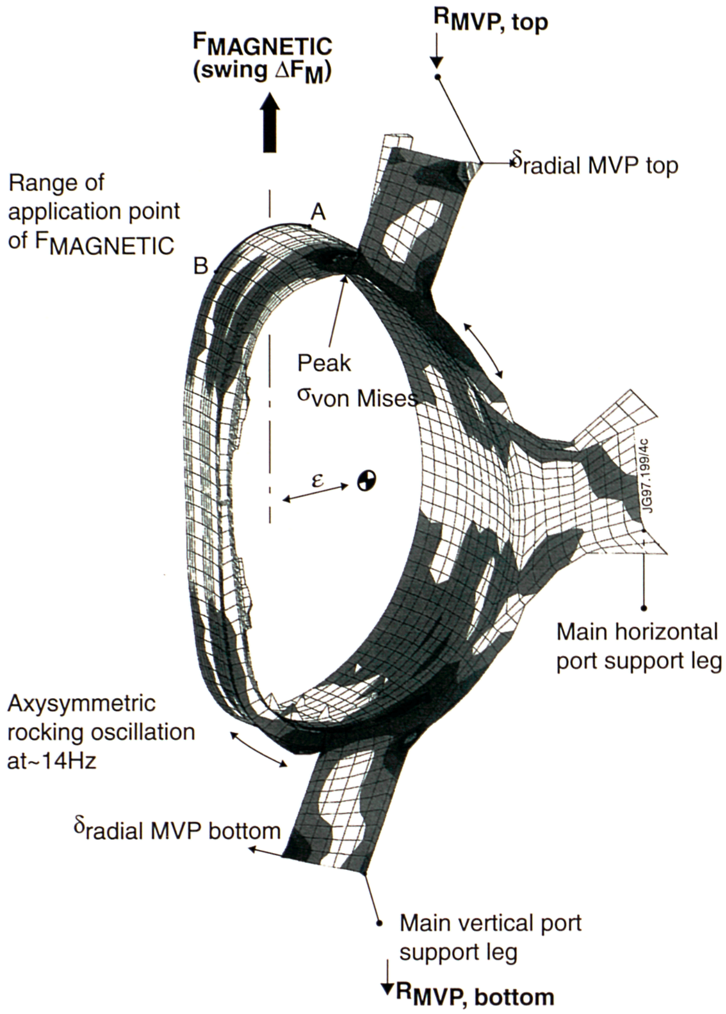


Fig.11: Finite element model of the vacuum Vessel Rolling Motion

Plasma-Machine Interactions

Plasma instabilities, leading to fast plasma vertical displacement events (VDEs) usually followed by plasma disruptions, can generate large forces on the vacuum vessel and on in-vessel components. It had always been assumed that these forces were toroidally symmetric, and so the main concern were the total forces on the vessel. In early operation with the Mark I divertor, toroidal asymmetries of the force distribution were observed. A new topology of such forces was seen, leading to sideways movements of the vessel of several millimetres.

During the 1995/96 shutdown, it was discovered that these sideways motions caused damage to the seals of the two rotary valves connecting the main horizontal port (MHP) beam injection boxes. A new system of hydraulic lateral restraints linking the MHP to mechanically fixed bridges between the mechanical structure the transformer limbs was installed (Fig.10). These formed a complete belt surrounding the vessel, and was expected to lead to an appreciable reduction of radial displacement during VDEs.

The same type of VDE continues to occur with Mark II divertor with radial displacements of up to 7mm, in spite of the fact that the lateral restraints worked according to design specifications. The lateral force was higher than anticipated (~400 tonnes instead of ~150 tonnes), and therefore, another dumping mechanism must be present. Preliminary calculations showed that magnetic dumping of the vessel moving across magnetic filed lines is far more effective than the installed hydraulic restraints. Further work is underway to better assess the mechanism of these events.

The response of the JET vessel to both vertical and horizontal forces has been analysed in a considerable number of disruptions. In particular, the rolling motion response to vertical forces has been analysed statistically and dynamically with a particular model. A series of analyses has been carried out to check the consistency of simulations with observations of forces and displacements during the last campaign. Typically, both observed and calculated ratios of port displacement/ support force are in the range of 0.9~1.1mm/MN, depending on position and timescale of the load. An example of the results of the model of the vacuum vessel rolling motion is shown in Fig.11.

The knowledge acquired so far on these events is insufficient to devise means to prevent them. However, this type of interaction between plasma structures should be considered as a problem to be seriously addressed both in present tokamaks and in ITER.

Power Supplies

The electric power to the JET device during an experimental pulse is counted in hundreds of megawatts.

An agreement with the Generating Boards allows up to 575MW of pulse power to be taken directly from the 400kV grid, which after transformation down to 33kV is fed to the JET loads through a system of circuit breakers.

Two flywheel generators are used to provide the peak power for the toroidal magnetic field coils and ohmic heating circuit. Each of the generators has a rotor 9m in diameter weighing 775 tonnes. Between pulses, 8.8MW pony motors are used to increase the speed of rotation. When power is required for a JET pulse, the rotor windings are energised and the rotational energy of the flywheel is converted into electrical energy. On slowing down from the maximum speed of 225rpm to half speed, the generators can reach deliver 2.6GJ of energy with a peak power output of 400MW.

Heating and Current Drive Systems

Neutral Beam Heating

During 1996, the Neutral Beam heating system once more played a major role in the successful and diverse experimental programme of JET. There was heavy involvement in the operational programme and most of the year was spent in bringing the system towards its 'nominal' installed power of >19MW, and a number of problems had been overcome.

The number of discharges during 1996 with NB injection was the highest of any campaign. Due to the emphasis on establishing regimes, of high fusion performance in preparation for DTE1, the proportion of pulses with high power NB injection (>5MW) was also the greatest during this period. Only at the highest power levels (>18MW) was the number and proportion of pulses less than in the 1995 campaign; comparison with that period is appropriate since the injectors were configured similarly with respect to the number of installed PINIs of each type.

The basic configuration of two Neutral Beam Injectors (eight beam-lines each) has not been modified. However, operational flexibility was enhanced by further alleviation of limitations arising from 'shine-through' exposure of in-vessel structures and from deposition of re-ionised beam particles on torus entry duct surfaces, by installing CFC tiles at appropriate locations. The beam-line calorimeters were replaced with new ones of enhanced capability in power density loading ($20MWm^{-2}$), thus allowing longer pulses in asynchronous operation (no beam into the plasma). All 16 beam lines were made compatible with tritium and the Active Gas Handling System can now supply the injectors with deuterium and/or tritium. During DTE-1, eight beam-lines will be operated at 80kV, 55A, supplied with deuterium (13.6MW) and eight beam lines supplied with tritium, will be operated at 160kV, 30A (12MW).

Radio Frequency Heating

The ion cyclotron resonance frequency (ICRF) heating system is used for high power centralised heating of the plasma, with increased emphasis on Fast Wave Current Drive studies with the new antennae. The localisation depends mainly on the magnetic field and is insensitive to parameters such as density and temperature. Wide-band operation (23-57MHz) allows variation in both the choice of minority ion species heated (H or He^3 at present, D in the future D-T phase) and the localised position of the heating.

New ICRF antennae (Fig.12) have been optimised to the geometry of the divertor plasmas. Their location in the torus has been revised to give four arrays of two adjacent antenna. Each array has four RF radiating conductors or straps, which provide an enhanced radiated spectrum. Variation in the relative phase of the RF currents in the straps allows this spectrum to be varied for both heating and current drive experiments.

The power deposition can be located on-axis or off-axis depending only on the ion species and the frequency chosen with respect to the magnetic field. The fast magnetosonic wave excited by the antennae can access dense plasmas. Therefore, there is no difficulty in providing central heating at the high densities relevant for reactor operation. The antennae are multi-strap units in which the currents can be phased to launch waves either with no net toroidal directivity for heating purposes, or with up to 75% toroidal directivity for both ion and electron current drive applications.

During the 1995 campaign, the average power coupling to the plasma from the ICRF antennae was significantly less than anticipated. Therefore, the antennae were removed during the shutdown to incorporate a number of modifications. Additional capacitance was added to the cross-over straps linking the inner conductors to the incoming vacuum transmission lines, the antennae were displaced 6mm inwards and the lower straight section of the limiter sections were modified to better follow the plasma curvature. Moreover, several modifications were introduced in the electronic circuitry, such as the addition of a conditioning mode, to maximise energy deposition without risking antenna damage. As a result, 15MW of coupled power to H-mode plasmas was achieved in dipole phasing during 1996.

Lower Hybrid Current Drive

The Lower Hybrid Current Drive (LHCD) system, operates at 3.7GHz and is capable of driving a significant fraction of the toroidal current in the plasma. This is achieved

Neutral Beam Heating

The two JET neutral beam systems have been designed for long (~10s) beam pulses. They have the unique feature that each injector consists of eight beam sources in a single integrated beamline system connected to the torus. The first beam sources were designed to operate at accelerating voltages up to 80kV and in 1990 one system was substituted with units capable of operating up to 140kV. In addition, this box was also converted to operate with helium (^3He and ^4He) beams during 1990. In the D-T phase, one unit will be converted for operation with tritium at 160kV.

Each system is connected to the torus by a long narrow duct through which up to 12MW of power can be directed.

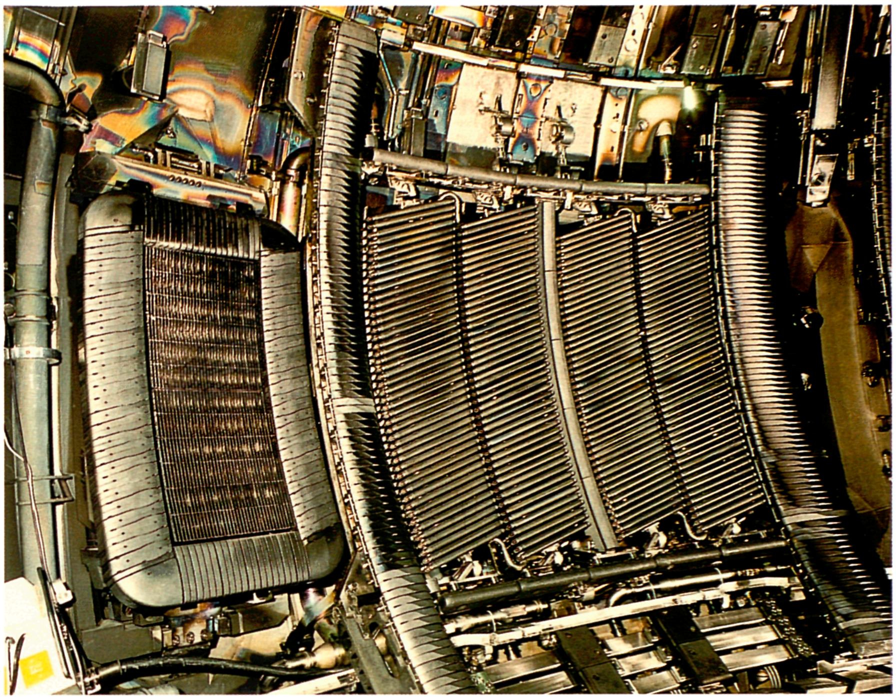


Fig.12: The LHCD launcher together with one module of the ICRF antennae

by launching an RF wave predominantly in one toroidal direction. This wave accelerates the high energy electrons in the plasma and so drives a current. It may be used to stabilise sawtooth oscillations, thereby increasing central electron temperature. It is this system for controlling the plasma current profile, which is considered to be the main tool to stabilise high beta poloidal plasma with a large bootstrap current (the so-called advanced tokamak scenarios).

Lower Hybrid Current Drive (LHCD) has been used during the 1996 campaign mainly for current profile control in shear optimisation scenarios. Reliable plasma formation with a fast plasma current ramp rate and control of the internal inductance have been supported by applying LHCD during the current ramp-up phase.

Formation of an internal transport barrier and improved central thermal electron confinement have been obtained with LHCD alone. Reliability and flexibility of LHCD operation have been improved by various upgrades of the plant and the control systems. Active coupling control has been expanded to plasma position and shape control on the reflection coefficient. Gas puffing though a dedicated feed near the LHCD launcher allowed good coupling to be achieved with a large plasma-launcher distance and the launcher being kept retracted behind protection limiters.

Radio Frequency Heating

Ion Cyclotron Resonance Frequency (ICRF) heating has been chosen for JET and the wide operating frequency band (23-57MHz) allows the system to be operated with the various mixes of ion species required in the different phases of the scientific programme and to choose the location where the heating in the plasma occurs.

The ICRF heating system has been designed in eight identical modular units. Each unit is composed of a tandem amplifier chain, a network of coaxial transmission lines and matching elements and finally on antenna located in the vacuum vessel on the outer wall. The eight RF generators produce a maximum output power of 32MW. The net power coupled to the plasma has reached 22.7MW, compared with theoretical limit of 24MW.

Diagnostic Systems

The status of JET's diagnostic systems at the end of 1996 is summarised in Table 4 and the layout in the machine is shown in Fig.13. Operational experience on the diagnostics has been good and most systems have operated automatically with minimal supervision. The resulting measurements have provided essential information on plasma behaviour.

SYSTEM	DIAGNOSTIC	PURPOSE	ASSOCIATION
KB1	Bolometer cameras	Time and space resolved total radiated power	IPP, Garching
KB3D	In-vessel divertor bolometers	Time and space resolved radiated power	JET
KB4	In-vessel main plasma bolometer	Time and space resolved radiated power	JET
KC1	Magnetic diagnostics	Plasma current, loop volts, plasma position, shape of flux surfaces, diamagnetic loop, fast MHD	JET
KC1D	Magnetic pickup coils	Plasma geometry in divertor region	JET
KD1D	Calorimetry of Mark I divertor target	Power balance of divertor plasma	JET
KE1E	Edge Thomson scattering	T_e and n_e in scrape-off layer	JET
KE3	LIDAR Thomson scattering	T_e and n_e profiles in core plasma	JET and Stuttgart University
KE4	Fast Ion and alpha-particle diagnostic	Space and time resolved velocity distribution of alpha particles and fast ions	JET
KE9D	Divertor LIDAR Thomson scattering	T_e and n_e profiles in divertor plasma	JET
KF1	High energy neutral particle analyser	Ion energy distribution up to 3.5MeV (ICRF minority and fusion products)	Purchased from Ioffe, St Petersburg
KG1	Multichannel far infrared interferometer	$\int n_e d\ell$ on four vertical chords and four horizontal chords – electron density	CEA, Fontenay-aux-Roses
KG3	O-mode microwave reflectometer	n_e profiles and fluctuations	JET and FOM, Rijnhuizen
KG4	Polarimeter	$\int n_e B_p d\ell$ on four vertical and four horizontal chords – poloidal magnetic field	JET and CEA, Fontenay-aux-Roses
KG6D	Divertor microwave interferometer	$\int n_e d\ell$ on sightline across the divertor plasma	JET
KG7D	Divertor microwave comb reflectometer	Peak n_e on sightline across divertor plasma	JET and CFN IST, Lisbon
KG8A	E-mode reflectometer	Measurement of n_e fluctuations and profiles in edge and SOL	JET and CFN IST, Lisbon
KG8B	Correlation reflectometer	Density fluctuations	JET
KH1	Hard X-ray monitors	Runaway electrons and disruptions	JET
KH2	X-ray pulse height spectrometer	Monitor of T_e, impurities and LH fast electrons	JET
KJ3	Compact, re-entrant soft X-ray camera	MHD instabilities, mode identification, plasma shapes and impurity transport	JET
KJ4	Compact, in-vessel soft X-ray camera	MHD instabilities, mode identification, plasma shapes and impurity transport	JET
KJ5	Active phase, soft X-ray cameras	MHD instabilities and vertical position sensing, DT compatible	JET
KJ6	Compact VUV camera	Divertor view in VUV	JET
KK1	Electron cyclotron emission spatial scan	$T_e(r,t)$ with scan time of a few milliseconds	NPL, UKAEA Culham and JET
KK2	Electron cyclotron emission fast system	$T_e(r,t)$ on microsecond time scale	FOM, Rijnhuizen
KK3	Electron cyclotron emission heterodyne	$T_e(r,t)$ with high spatial resolution	JET
KK4D	Electron cyclotron absorption	$n_e T_e$ profile on sightline across divertor plasma	JET
KL1	CCD viewing and recording	Plasma viewing	JET
KL1E	Endoscopes	To allow an unrestricted view of the divertor in the visible and IR	JET
KL2	Impurity flux camera	Impurity influx from the divertor targets with high spatial resolution	JET
KL3A	Infra-red camera (1 dim)	Divertor tile temperature profiles	JET
KL3B	Infra-red camera (2 dim)	Divertor tile temperature profiles with high dynamic range	JET
KL4	Infra-red protection diodes	Machine protection – divertor tile temperature	JET
KL5	Fast spectroscopic cameras	Fast D_α measurements at two toroidal locations for ELM studies	JET
KL6	Colour view of divertor tiles	Colourimetry – used for erosion/redeposition measurements	JET
KM2	14MeV neutron spectrometer	Neutron spectra in D-T discharges, ion temperatures and energy distribution	UKAEA Harwell
KM3U	2.4MeV time-of-flight neutron spectrometer	Neutron spectra in D-D discharges, ion temperatures and energy distributions	JET and NFR, Studsvik

SYSTEM	DIAGNOSTIC	PURPOSE	ASSOCIATION
KM5	14MeV time-of-flight neutron spectrometer	Neutron spectra in D-T discharges, ion temperatures and energy distribution	NFR, Gothenburg
KM7	Time-resolved neutron yield monitor	Triton burnup studies	JET and UKAEA, Harwell
KM9	MPR Neutron spectrometer	Neutron spectra	NFR, Uppsala
KN1	Time-resolved neutron yield monitor	Time resolved neutron flux	UKAEA, Harwell
KN2	Neutron activation	Absolute fluxes of neutrons	UKAEA, Harwell
KN3U	Neutron yield profile monitor and FEB	Spatial and time resolved profiles of neutron flux and fast electron Bremsstrahlung	JET and UKAEA, Harwell
KN4	Delayed neutron activation	Absolute fluxes of neutrons	Mol
KR2	Active phase, neutral particle analyser	Ion distribution function, T(r) and H/D/T flux ratios	ENEA, Frascati
KS1	Active phase spectroscopy	Impurity behaviour in active conditions	IPP, Garching
KS3	H-alpha and visible light monitors	Ionisation rate, Z_{eff}, impurity fluxes from wall and divertor	JET
KS4	Charge exchange recombination spectroscopy (using heating beam)	Fully ionized light impurity concentration, $T_i(r)$ and rotation velocities	JET
KS5	Active Balmer alpha spectroscopy	Neutral beam deposition, plasma effective charge and motional Stark measurement (for internal magnetic field)	JET
KS6	Bragg rotor X-ray spectroscopy	Monitor of low and medium Z impurity radiation	UKAEA, Culham
KS7	Edge charge exchange	Uses polarisation of Stark components of beam emission to measure pitch angle of magnetic field	UKAEA, Culham
KS8	Motional Stark effect diagnostic	Multichannel measurement of edge poloidal rotation, ion temperature and impirity density	JET, UKAEA, PPPL
KS9	Polarisation resolved passive spectroscopy	Radially located source measurements from Zeeman splitting of lines	JET
KT1D	VUV spatial scan of divertor	Time and space resolved impurity densities	JET
KT2	VUV broadband spectroscopy	Impurity survey	UKAEA, Culham
KT3	Active phase CX spectroscopy	Fully ionized light impurity concentration, $T_i(r)$, rotation velocities and divertor sources	JET
KT4	Grazing incidence XUV broadband spectroscopy	Impurity survey	UKAEA, Culham
KT5P	Divertor gas analysis	Analysis of divertor exhaust gasses	
KT6D	Poloidal view, visible spectroscopy of divertor plasma using periscopes	Impurity influx, 2D emissivity profile of spectral lines	JET
KT7D	VUV and XUV spectroscopy of divertor plasma	Impurity influx, ionization dynamics, electron temperature and density	JET
KX1	High resolution X-ray crystal spectroscopy	Central ion temperature, rotation and Ni concentration	ENEA, Frascati
KY3	Plasma boundary probes	Vertical drives for reciprocating Langmuir and surface collector probes	JET and UKAEA, Culham
KY4D	Langmuir probes in divertor target tiles and limiters	n_e and T_e at the divertor and limiters	JET
KY5D	Fast pressure gauges	Neutral flux in divertor region	JET
KY6	50kV lithium atom beam	Electron density in scrape-off layer and plasma edge	JET
KY7D	Thermal helium beams	n_e and T_e in the divertor plasma (together with KT6D)	JET
KZ3	Laser injected trace elements	Particle transport, τ_p, impurity behaviour	JET
Kα1	Thin foil charge collectors	Lost alpha-particle detection	JET
Kγ5 & 8	Gamma rays	Fast ion distribution	JET

Table 4: Status of JET Diagnostics Systems, December 1996

Control and Data Management

The JET Control and Data Management System (CODAS) is a fully integrated computer-based system. A network of UNIX-based computers is used for controlling, monitoring, data acquisition and storage of data. This network is also used to analyse the data from the tokamak, its power supplies, auxiliary equipment and diagnostic devices. CODAS also provides the following common services: Network Information Services (NIS), Mail, file servers, printing, network

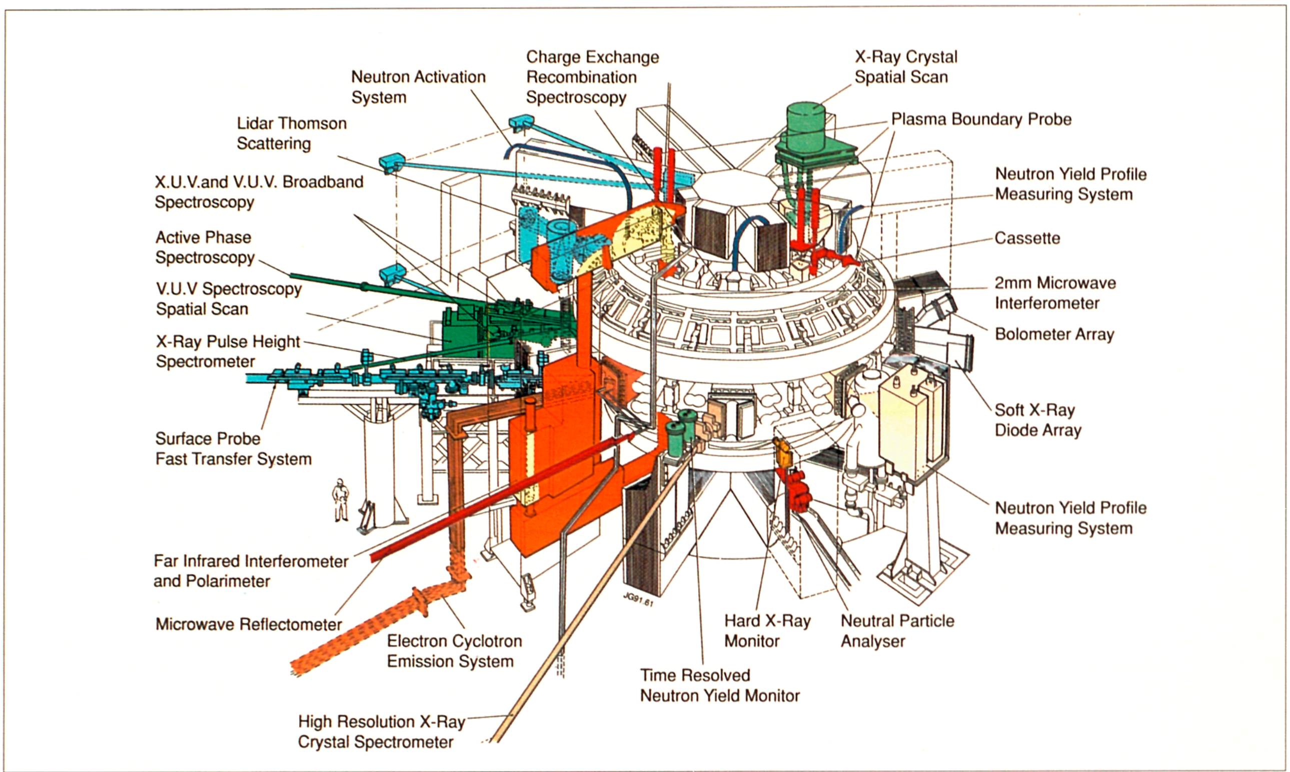


Fig.13: General layout of diagnostics in the machine

monitoring and off-line programme development. These services have grown further and over 120 systems are now in regular use.

JET components and diagnostic devices are grouped into a number of sub-systems. Sub-systems that include parts of the tokamak and its auxiliary systems are referred to as control sub-systems; and diagnostic devices are grouped into diagnostic sub-systems. Each sub-system is controlled and monitored by one dedicated computer interfaced to the machine and its diagnostics through CAMAC and/or VME instrumentation. Embedded front-end intelligence is implemented through CAMAC and VME-based microprocessors for real-time applications.

Several improvements have been implemented to make operation activities more efficient. These include a new programme, the Object Monitoring System (OMS), substantially reduces the time for a particular plant mimic to appear on the screen; the count-down programme has been redesigned to make better us of the UNIX computer network; and in-vessel video images are now taped routinely on the six video recorders of the endescope diagnostic, showing views of the divertor. Significant improvements in the ease of operation has been achieved by the use of the Real Time Power Control System, which controls the power of the ICRF, LHCD and NB systems in following the pattern defined for the pulse.

The mainframe computing service is based on an IBM 3090/300J three-way processor mainframe with two vector facilities. There are 360 Gigabytes (GB) of disc storage and a further 7200 GB of automated cartridge tape storage. JET passed two

Control and Data Acquisition

Due to the high number of components and their distribution throughout a large site, the operation and commissioning of JET is supported by a centralised Control and Data Acquisition System (CODAS). This system is based on a network of minicomputers interfaced to the experiment through distributed front-end instrumentation (including front end micro-processors) and signal conditioning modules. The various components have been logically grouped into subsystems with each one controlled and monitored by a computer. After a pulse, all the information from the subsystem is merged together into a single file on the storage and analysis computer. This file is then transmitted to the IBM mainframe computer for detailed analysis. A summary of information from the JET pulses is held in the JET Survey Data Bank.

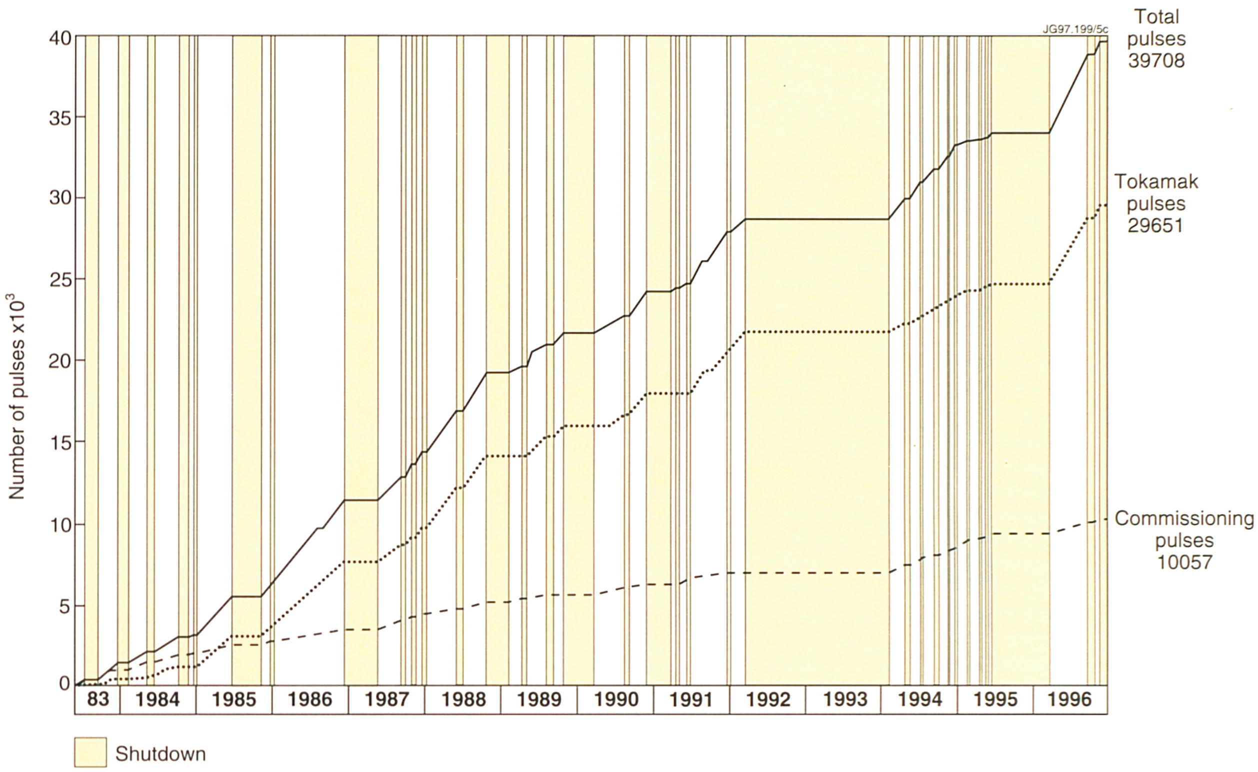


Fig.14: Culminative total of JET pulses: 1983-1996

symbolic milestones in 1996: the total raw data collected and archived has exceeded 1 Tera-byte (~1.1 x 10^{12} bytes) and the number of public PPFs written has exceeded one million. During 1996 operations, there was a continuing increase in the amount of data with JET Pulse File sizes up to 405 MB per pulse, yielding up about 8 GB of data each day of operation.

The data is transmitted from the CODAS UNIX systems to the IBM at speeds of about 600 kilobytes per second ensuring that JET data is available for analysis on the mainframe promptly after collection on the CODAS systems. The development of a very sophisticated data archiving and retrieval system based on a cache of 50 GB of on-line disc backed by tape storage on the ATL currently accommodate over 1200 GB of raw data (JPF), which is compressed by a factor of about 2.5 for storage. The total data collected in 1996 was 524 GB, compared with less than 200 GB in each of the previous two years. The system gives almost instant access to any JPF data that is available on disc (typically about 3 weeks data production). Data less recently accessed is restored automatically from cartridge tape and average time to access data is less than one minute for any shots back to original start up in 1983.

Summary of Operations

The shutdown for the installation of the Mark II divertor ended on the 28 March 1996. The Restart period then started and was completed on 10 June 1996. Mark II divertor operations continued until 28 September 1996. At this time, a further shutdown occurred until 26 October for the divertor bypass filling. Restart after this minor shutdown was much shorter and took until 22 November. Task Force operations of the Mark II divertor with bypass filling lasted until 10 December 1996, and was curtailed due to a water leak, which developed in the Octant No. 8 neutral beam system.

There were 2365 Task Force pulses during the year, with a success rate of 84%. The distribution between the Task Forces was: Divertor Physics Task Force (D) - 34.9%; High Fusion Performance Task Force (H) - 30.6%; and ITER Physics and Performance Optimisation Task Force (P) - 34.5%.

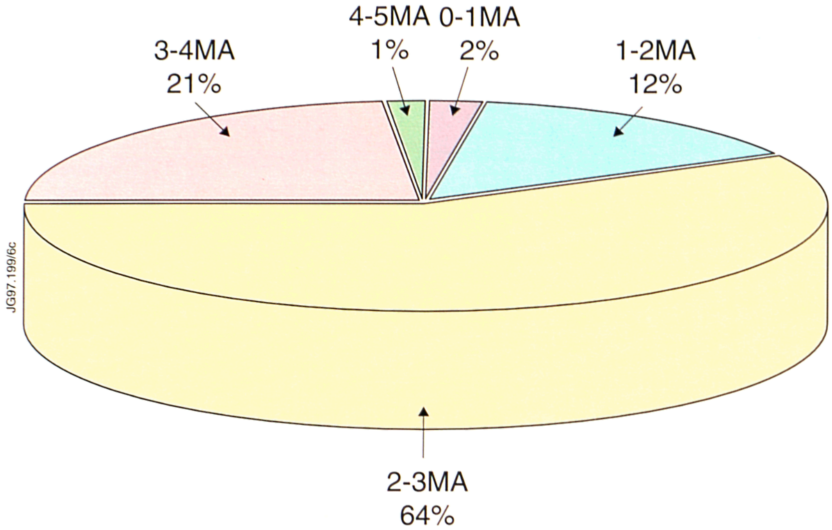


Fig.15: Plasma current distribution for 1996

The total number of pulses in 1996 was 3929, including Task Force , Restart and technical commissioning pulses. The overall distribution over the 1983-96 period is shown in Fig.14. An analysis of the plasma current distribution shows that operations in the range 2-3MA continued to be routinely established and represented 64% of all plasma pulses (Fig.15).

Technical Developments for Future Operations

Considerable effort was devoted during the year to the design and procurement of equipment for installation on the machine during future shutdown periods. Reference should be made to the section on the Future Programme of JET to relate these technical developments to the overall JET programme.

Tritium Handling

The Active Gas Handling System (AGHS) is a full gas reprocessing plant, designed to collect gases from the torus, to remove impurities from hydrogen, to isotopically separate the hydrogen gas into streams of protium, deuterium and tritium, to store the deuterium and tritium in U-beds for re-use, and to inject deuterium and tritium back into the torus. Isotope separation makes use of cryo-distillation and gas chromatography. The system is located in a separate building, and a schematic of the system is show in Fig.16. It was designed for a maximum daily throughput of up to 5 moles of tritium, 15 moles of deuterium and 150 moles of protium. It was installed in compliance with a strict quality assurance programme and went through an extensive phase of inactive testing. Tritium commissioning was performed in two steps. Trace tritium commissioning with about (~0.08g) was performed with a tritium-hydrogen gas mixture. Full tritium commissioning with about 3g of tritium started in September 1996 and is continuing, to test the complete process using all sub-systems. It should be completed ready for operation in DTE-1 in Summer 1997.

JET is required to satisfy the United Kingdom Atomic Energy Authority (UKAEA - the host organisation) that adequate safety standards exist prior to tritium operation. The safety submission for DTE1 was submitted for review by the Safety Directorate Group of AEA Technology on behalf of the UKAEA. The safety case sets out the design safety principles, identified potential accident scenarios and assessed these against both deterministic and probabilistic dose/frequency criteria, as laid down by the UK Health and Safety Executive.

The safety case demonstrated that JET complies with relevant standards, and approval was granted by the appropriate safety and regulatory authorities for the D-T operation of JET with up to 20g of tritium in the torus systems and for the

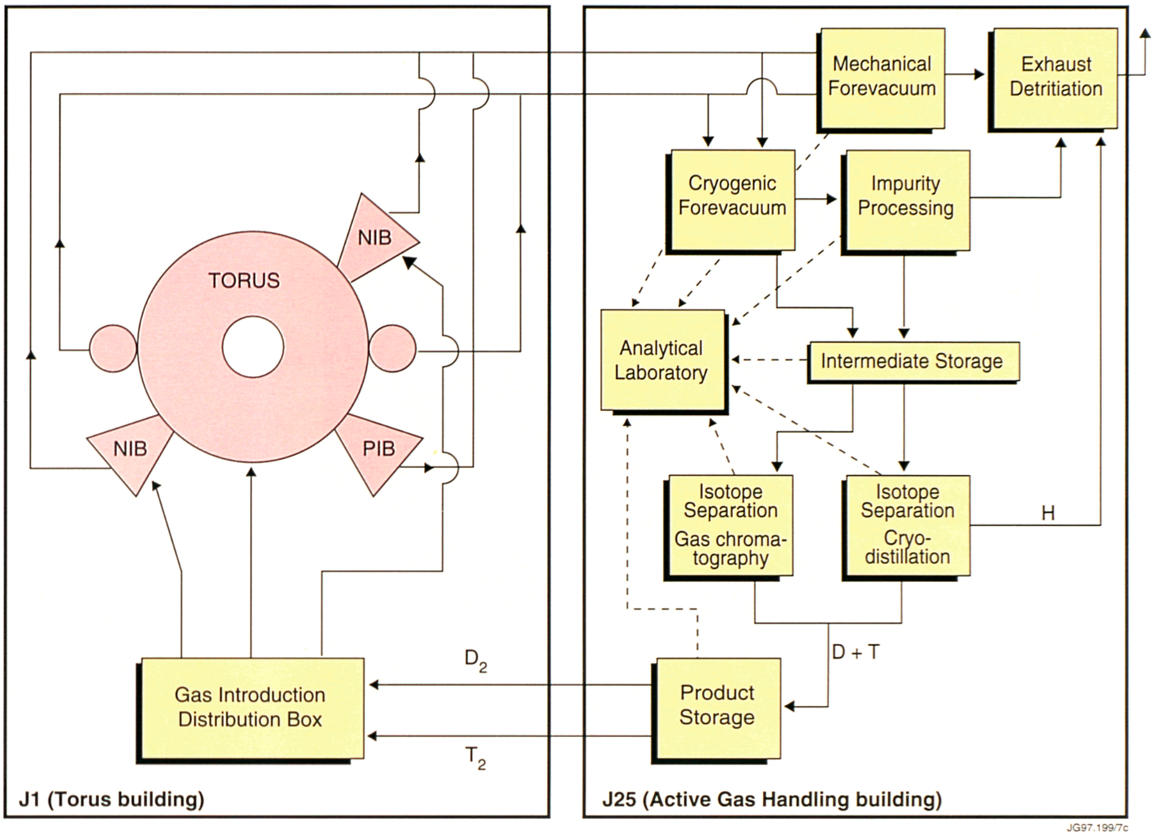


Fig.16: Schematic of Active Gas Handling System

generation of 14MeV neutrons within a limit of 2.5×10^{20} (the programme plan is for 2×10^{20}). This permits the DTE1 series of experiments to be performed in accordance with the step-wise approval set down in the safety case.

Plans for D-T Operation

A Working Party was set up in 1995 to propose plans for the DTE-1 Experiments. The programme was prepared within the constraints of a limit of 2×10^{20} D-T neutrons and a programme duration of 3-4 months. The objectives remain essentially unchanged and these are summarized, as follows:

(a) High fusion power demonstration in a reactor-like configuration, with Q approaching unity (Q~1) for over one energy confinement time. This should allow the observation and study of alpha-particle effects, at least in the plasma centre;

(b) D-T physics of a reacting divertor tokamak, in an ITER like geometry, including H-mode threshold behaviour;

(c) Demonstration of a reactor relevant fully remote handling operation (i.e. replacement of the divertor target assembly);

(d) Operation of the Tritium Processing System integrated with a reacting tokamak (the JET Tritium Processing Facility is reactor scale and uses reactor relevant technology).

The technical preparations required for DTE1 consisted essentially of bringing existing systems to full tritium readiness and producing the necessary documentation to fulfil JET's obligation for tritium operation to satisfy the UKAEA (the Host Organisation) that the arrangements conform to required standards.

The main areas in which work was undertaken were:

- Preparation of the Safety Case;
- Completion and commissioning of the tritium plant;

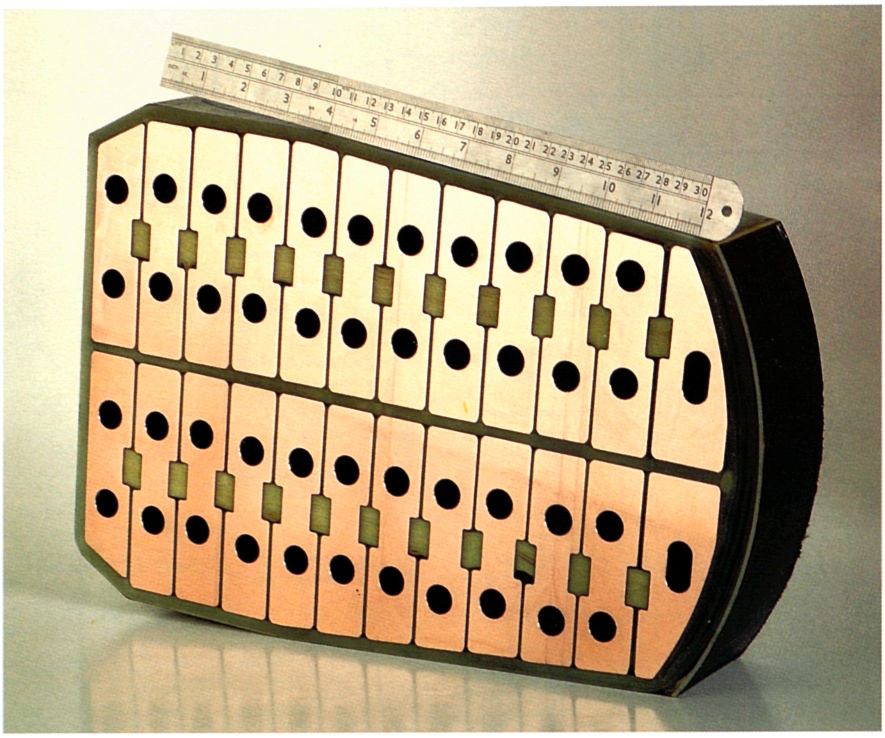


Fig.17: Slice cut from a toroidal field coil for inspection and for test sample production

- Completion of installed systems to full tritium specification;
- Commissioning of tritium related safety systems;
- Establishing written operational procedures for tritium related systems;
- Training of staff for operation of tritium related systems.

Studies for Machine Performance Enhancement

In view of the extension of JET to the end of 1999, studies have been undertaken on possible enhancement options of some of the sub-systems. It was considered that, the toroidal magnetic field could be increased from the present 3.45 Tesla to a value of ~4 Tesla. In addition, the output power of the neutral beam injectors could be improved by increasing the power supplies from 80kV at 60A to 120-140kV at 60A.

Toroidal Field to 4T

The strategy for operating the toroidal field coils is based on high reliability, long life and minimal risk. However, a reliability analysis performed in 1992/93, showed that only a small percentage of the coil's life has been used since JET started operation in 1983. Therefore, with a moderately increased risk and an acceptable reduction of life, it was thought that operation of the TF coils at up to 4T should be possible. Finite element stress analysis has shown that for a variety of high performance scenarios, the shear stresses on the interturn insulation and tension on the copper brazed joints are well within their design capability and the evaluation of the manufacture documentation, including tests on insulation and on brazed joint samples and on the prototype coil, indicate an acceptable margin of safety at 4.0T.

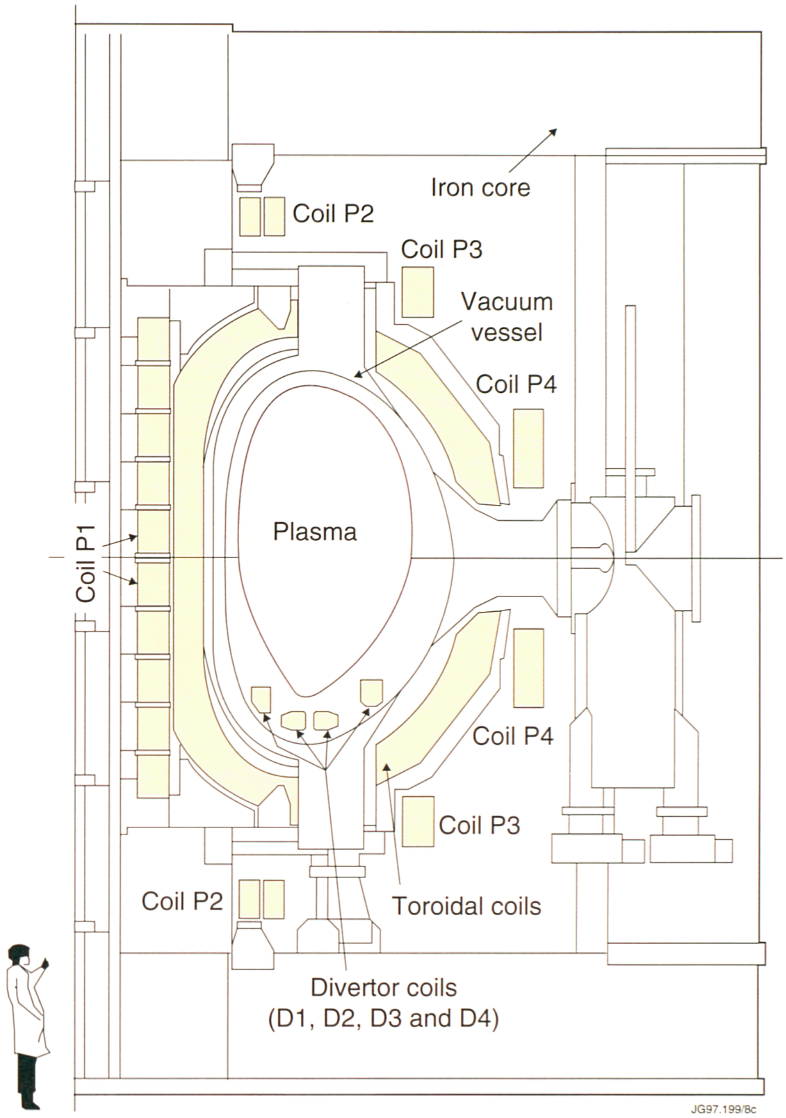
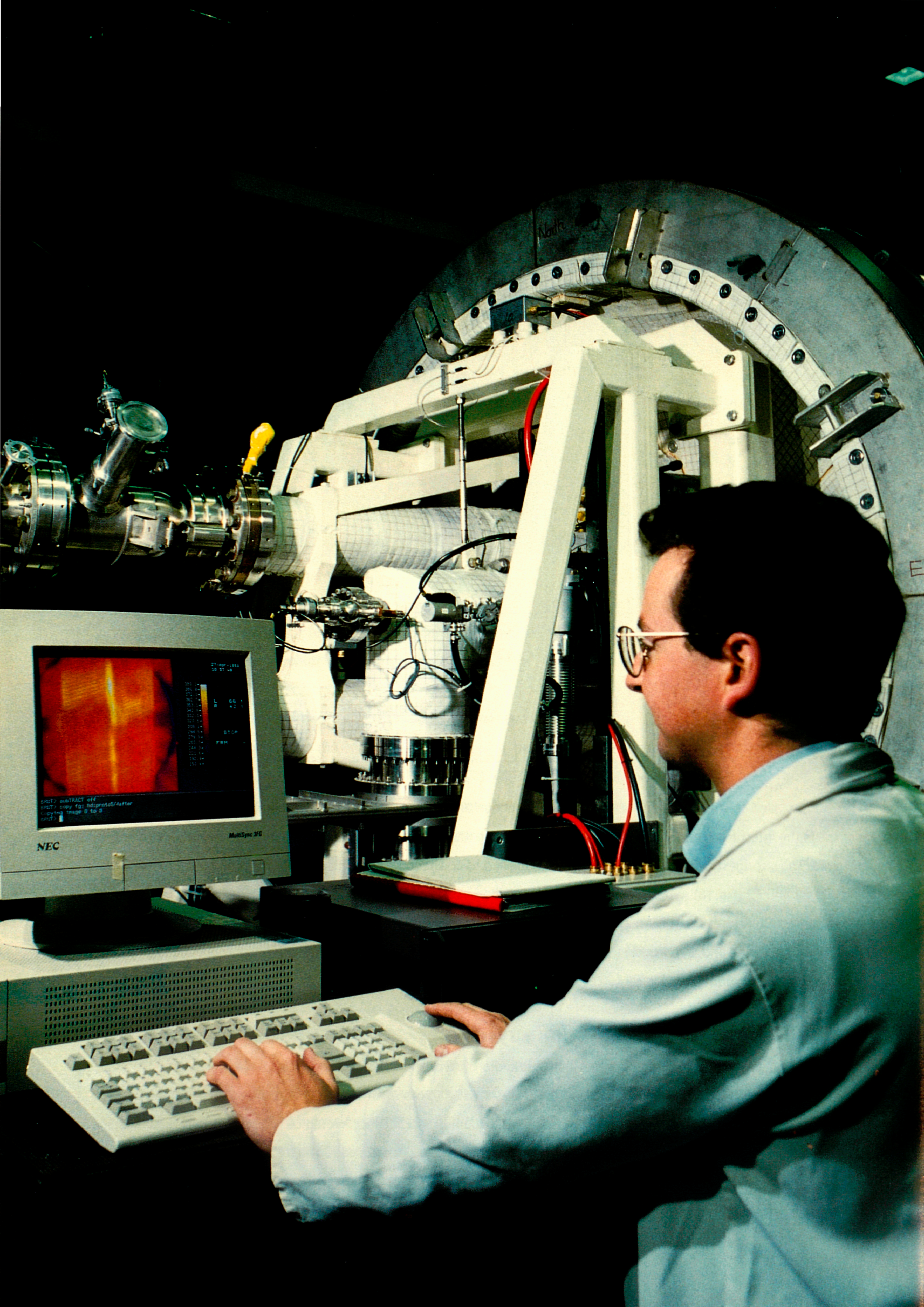


Fig.18: Cross-section showing the toroidal, poloidal and divertor coils

A previously failed coil has been cut for inner visual inspection and to extract samles (Fig.17) and is now under testing for shear stress in the interturn insulation. If these results support the finite element calculations, operations above 3.45T should be approved. The strongest contribution to the out-of-plane forces on the toroidal coils are the magnetic field created by the shaping coil P2 and P3 (Fig.18), which have an essential function in establishing X-point configurations, plasma elongation and triangularity. Therefore, there is an apparent conflict between physics requirements and the desire to limit the forces exercised on the machine and, in particular, on the toroidal coils. Ways to maintain high triangularity and good ICRF heating power coupling, which reduce the lateral forces on the toroidal coils are being investigated.

Enhancement of Neutral Beam Heating Systems

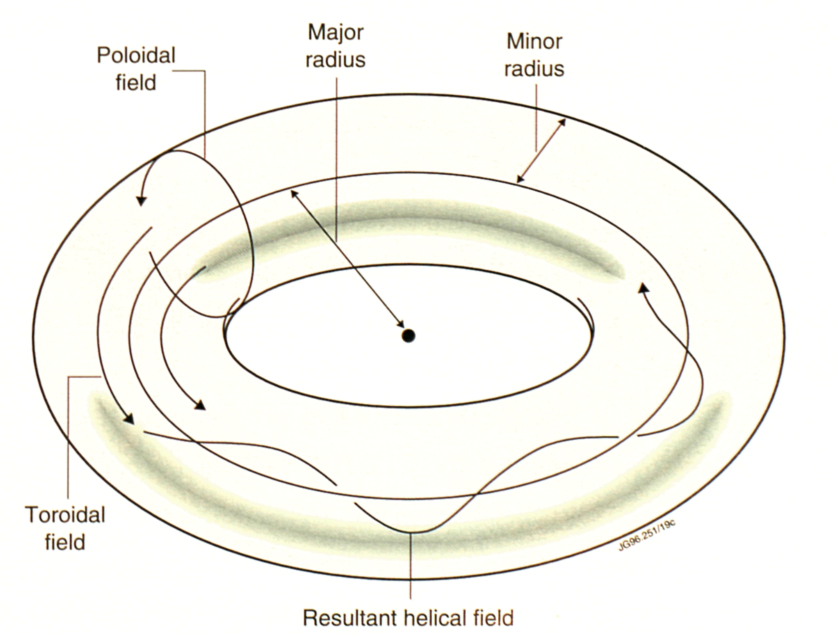
Experiments conducted in the Neutral Beam Test-bed, using a prototype modified accelerator structure have demonstrated the capability of increasing the ion beam current from the present 30A to 60A at 140kV. This would lead to an enhancement of injected power from 4 to 6MW per box (eight injectors). While minor modification would be required to the NB injectors, additional power supplies would be required, since the present supplies are for 60A at 80kV (or for 30A at 160kV). In view of costs, it has been decided to consider upgrading the power supplies to 60A at 120kV (which would somewhat reduce the delivered beam power).


NEC
MultiSync 3FG

Scientific Advances during 1996

Introduction

The overall objective of the Project is to study plasma in conditions and with dimensions close to those needed in a fusion reactor. The central values of temperature, density and energy confinement time required for a reactor operating with deuterium and tritium are such that the fusion triple product, $(n_i\tau_E T_i)$, must exceed the value of $5x10^{21}m^{-3}skeV$. Typical individual values for these parameters, in a reactor, are central ion density (n_i) of $2.5x10^{20}m^{-3}$, central ion temperature (T_i) of 10-20keV and a global energy confinement time (τ_E) of 1-2 seconds. With ohmic heating alone in JET, temperatures of 3keV and 4keV for the ions and electrons, respectively, densities of $4x10^{19}m^{-3}$ and energy confinement times of 1s are the limits that have been achieved. These parameters were obtained simultaneously during one discharge and resulted in a fusion product of $1.2x10^{20}m^{-3}keVs$. However, higher peak values of electron and ion temperature have



Magnetic Field Configuration

The toroidal and poloidal magnetic fields combine to form helical magnetic field lines, which define a set of magnetic surfaces. As the strengths of the magnetic fields vary across the minor cross-section of the machine, the pitch of the field lines vary and usually decrease with increasing minor radius. The number of turns a field line must traverse around the major direction of the torus, before closing on itself, is denoted by the safety factor, q. Of special importance are the positions where q is numerically equal to the ratio of small integers, as these regions are specially sensitive to perturbations. Instabilities arising from these perturbations can result in enhanced energy losses.

In addition, the maximum plasma pressure, which can be maintained by a given magnetic field is dependent on the plasma current value. The effectiveness with which the magnetic field confines the plasma is given by β, which is defined as the ratio of plasma pressure to the magnetic field pressure.

JET can be operated with elongated plasma cross-section rather than circular. This enables larger plasma currents to be carried for given values of magnetic field, major radius and minor radius, as well as producing larger values of β.

been reached using additional radio frequency heating and neutral beam heating and combinations of these methods. Even so, these substantial increases in temperature were associated with a reduction in energy confinement time as the heating power was increased. Thus, gains in plasma temperature have been partly offset by degradation in energy confinement time. The fusion product values obtained have not shown the full gains anticipated over conditions with ohmic heating only. However, a substantial increase in the values of the fusion product has been achieved, by operating in the so-called magnetic limiter (X-point) configuration. During the 1991/92 campaign, values of 9-10x$10^{20}m^{-3}$skeV were obtained using up to 16MW of additional heating.

Higher values of temperature, density and energy confinement have been obtained individually in separate experiments, but not simultaneously during one discharge. These include peak ion temperature up to 30keV, energy confinement times up to 1.8s and central densities up to 4x$10^{20}m^{-3}$.

Breakeven

This condition is reached when the power produced from fusion reactions is equal to that necessary for maintaining the required temperature and density in the plasma volume.

Experimental Programme

The strategy of JET is to optimise the fusion product by building up a high density and high temperature plasma in the centre of the discharge, while still maintaining an acceptable high confinement time. These conditions should ensure that sufficient alpha-particles are produced with deuterium-tritium operation so that their confinement and subsequent heating of the plasma can be studied.

The original scientific programme of JET was divided into four phases. The Ohmic Heating, Phase I, was completed in September 1984 and Phase II - Additional Heating Studies - started early in 1985. By December 1986, the first part, Phase IIA, had been completed. The machine then entered a planned shutdown for extensive modifications and enhancements before the second part of the Additional Heating Studies, Phase IIB, which started in June 1987. The objective of this phase, from mid-1987 until late-1988, was to explore the most promising regimes for energy confinement and high fusion yield and to optimise conditions with full additional heating in the plasma. Experiments were carried out with plasma currents up to 7MA in the material limiter mode and up to 5MA in the magnetic limiter (X-point) mode and with increased radio frequency heating power up to 18MW and neutral beam heating power exceeding 20MW at 80kV. The ultimate objective was to achieve full performance with all systems operating simultaneously. Phase III of the programme on Full Power Optimisation Studies started in 1989 and was completed in early 1992. In 1991, JET's lifetime was prolonged by four years until the end of 1996. The extension was to allow JET to implement the new Pumped Divertor Phase of operation, the objective of which is to establish effective control of plasma impurities in operating conditions close to those of the Next Step. This programme will be pursued before the final phase of full D-T operations in JET.

Ignition

Ignition of a mixture of deuterium and tritium would be reached if the power produced by the alpha-particles (20% of the total thermonuclear power) released from the fusion reactions is sufficient to maintain the temperature of the plasma.

The 1991/92 experimental period concentrated on: optimisation of plasma performance; advancing understanding in certain key areas of tokamak physics, (such as: physics of the H-mode; energy transport and confinement; and transport of particles and impurities); and establishing the basis for pumped divertor and Next Step physics (including a Preliminary Tritium Experiment).

The machine entered a major shutdown in early 1992, which lasted throughout 1992 and 1993, to prepare the machine for the divertor phase of operation. During this long shutdown, the interior of the vacuum vessel was essentially replaced. In 1994/95, JET undertook its planned programme of operations to demonstrate effective methods of power exhaust and impurity control in conditions close to those envisaged for ITER.

In mid-1995, JET entered the ITER-EDA Support Phase of its International Thermonuclear Experimental Reactor (ITER) Support Programme. In mid-1996,the JET programme was further extended to the end of 1999. The purpose of this extension was to provide further data of direct relevance to ITER, especially for the ITER-EDA, before entering into its final phase of D-T operation. In particular, the extension will make essential contributions to the development and demonstration of a viable divertor concept for ITER: permit carrying out experiments using D-T plasmas in an ITER-like configuration, which will provide a firm basis for the D-T operation of ITER; and allow key ITER-relevant technology activities, such as the demonstration of remote handling and tritium handling.

Operating Modes

Under normal operating conditions the magnetic surfaces are nested inside each other. The edge of the plasma is defined by the magnetic surface which intersects the limiter. The only magnetic field lines intersecting the walls of the chamber are those beyond the region bounded by the limiters as shown in the diagram on the left. This is termed material limiter operation.

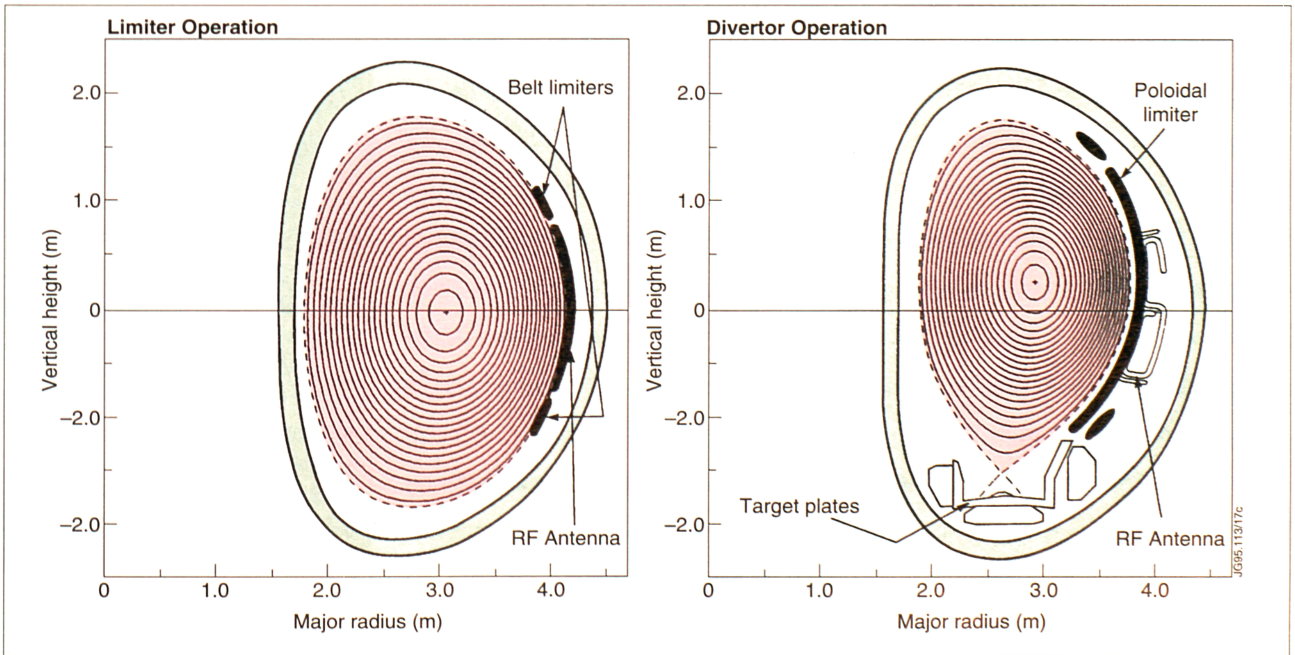
The magnetic field configuration on JET can be modified so that one of the closed surfaces near the limiter is opened up so that it intersects with the vacuum vessel wall. In this configuration, the magnetic separatrix is moved to within the vacuum chamber.

This so-called X-point configuration (or magnetic limiter) can be operated with the two nulls of the separatrix within the vacuum chamber (double null) or with only one inside (single null) as shown in the diagram on the right.

During X-point operation with additional heating, the plasma can behave, with respect to confinement, as though its edge were bounded by limiters. This is called the Low (L)-mode. Under certain circumstances, the plasma can be induced to behave in a different manner which produces better plasma confinement. This is termed the High (H)-mode of operation.

Main Scientific Results

The main objectives of the 1996 campaign were: to characterise plasma behaviour with the Mark IIA pumped divertor; to undertake a number of physics studies for



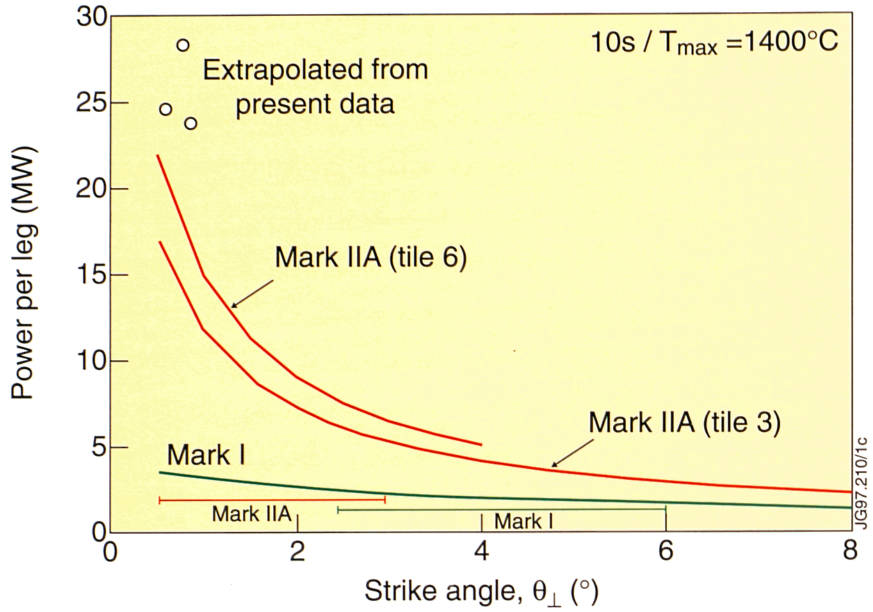


Fig.19: Power to the Mark IIA divertor compared with that to the Mark I divertor

ITER; and to prepare plasma scenarios for the D-T experiments (DTE1, scheduled for the Summer of 1997). Specifically, the campaign concentrated on ITER-relevant issues related to the "more-closed" Mark IIA divertor and, because of their importance for predicting ITER's ignition margin and fusion power output, the scaling of the threshold power for access to the H-mode regime and energy confinement in this regime. The preparation of high performance scenarios for DTE1 was also a high priority.

Characterisation of Behaviour with Mark IIA Divertor

The JET Divertor programme is based on three divertor configurations (Mark I, Mark IIA and an ITER-specific Mark IIGB) which are being introduced and tested sequentially. The divertor must fulfil three main functions: (i) exhaust plasma power at acceptable erosion rates; (ii) control plasma purity; and (iii) exhaust helium "ash" and provide density control. For ITER, successful divertor operation must be compatible with high confinement (H-mode) operation with Edge Localised Modes (ELMs).

During the 1995/96 shutdown, the relatively open Mark I divertor used for the 1994/95 experimental campaign was replaced by the Mark II divertor which comprises a common base structure capable of accepting various target assemblies. This allows the divertor geometry (degree of closure target configuration) to be varied and its effect on divertor and main plasma performance to be studied.

The Mark IIA target assembly is a moderate "slot" divertor which is significantly more-closed than Mark I, thus improving purity control and increasing atomic losses. Mark IIA allows operation under a wide range of plasma configurations and conditions and makes high power, high current operation possible on both the horizontal and vertical target plates.

Divertor

JET was originally configured as a "limiter Tokamak" where the edge of the plasma (the "last closed flux surface" - LCFS) was defined by contact with a material boundary called a limiter, which absorbs the exhaust power of the plasma. Since the edge of the plasma is quite hot, material is eroded by sputtering and the sputtered impurities enter the plasma relatively easily. This enhances radiative losses and dilutes the plasma, which lowers the fusion reaction rate.

The JET vacuum vessel and magnetic field system have been modified to operate in a "divertor" mode. The field configuration includes an "X-point" so that the LCFS (in this case designated the separatrix) bounding the main plasma does not intersect the wall. The power crossing the separatrix is transmitted in a thin layer called the scrape-off layer (SOL) to the divertor at the bottom of the vessel and is absorbed by the divertor "target plates". Divertor operation reduces the impurity content of the main plasma through a combination of effects. The divertor plasma is generally much cooler than the main plasma edge, so that sputtering and erosion are reduced. Moreover, impurities which are produced at the target plate tend to be retained in the divertor area by friction with the plasma streaming towards the divertor plates. In addition to controlling impurity content, divertor operation tends to allow higher SOL temperatures, thus facilitating access to high confinement regimes.

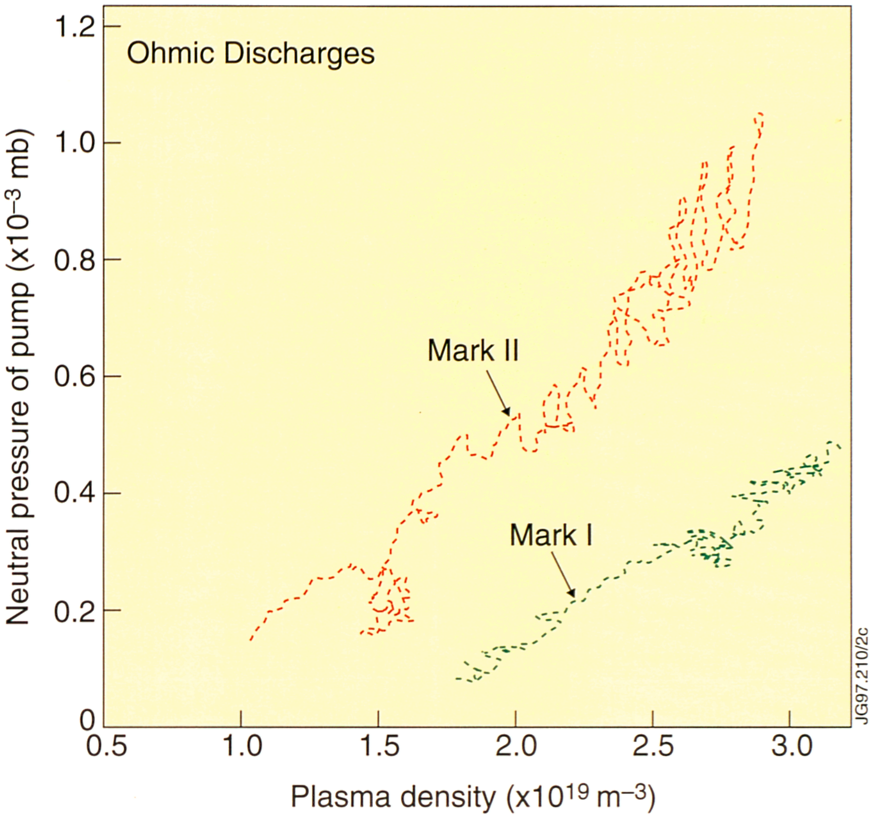


Fig.20: The neutral pressure at the pump as a function of density in both Mark I and Mark IIA divertors

The Mark IIA device behaved as expected for a more-closed divertor. It offered improved power handling over the Mark I divertor, withstanding JET's full heating power without overheating or localised sublimation of the graphite target material. This is indicated in Fig.19, which shows the better power handling capability, so that sweeping over the target tiles was no longer necessary.

In the Mark IIA divertor, higher neutral retention was predicted by calculations. This was confirmed by experiments, which showed that the neutral pressure at the pump increased by a factor of ~3 (Fig.20), the plasma was pumped 2-3 times more rapidly and the need to position the strike point over the pump throat was obviated.

In the divertor region, the effects of increased closure were clear from signs of increased neutral recycling and detachment of the divertor plasmas from the target at significantly lower main plasma density than with the Mark I configuration, a trend which was in agreement with code predictions. On the other hand, the effect of closure on main plasma confinement was, in general, small, although the more-closed configuration appeared to maintain good confinement to a slightly higher density normalised to a theoretically predicted (Greenwald) density limit. With the Mark IIA divertor, the time for injected trace neon to be pumped out was observed to be shorter, but the expected reduction in the level of intrinsic impurities in the plasma core did not occur, perhaps due to stronger interactions with the tile shoulders of the divertor, higher tile operating temperatures or greater tile coverage of the inner wall.

ELM

An ELM (Edge Localized Mode) is an edge instability which occurs in the high confinement (H-mode) regime. It affects a narrow region in the plasma edge and leads to a loss of particles and energy from the edge on a timescale ≤1 millisecond and therefore is a rapid, but transient, instability. However, ELM's can occur as repetitive instabilities which cause a reduction in the time-averaged energy and particle confinement time.

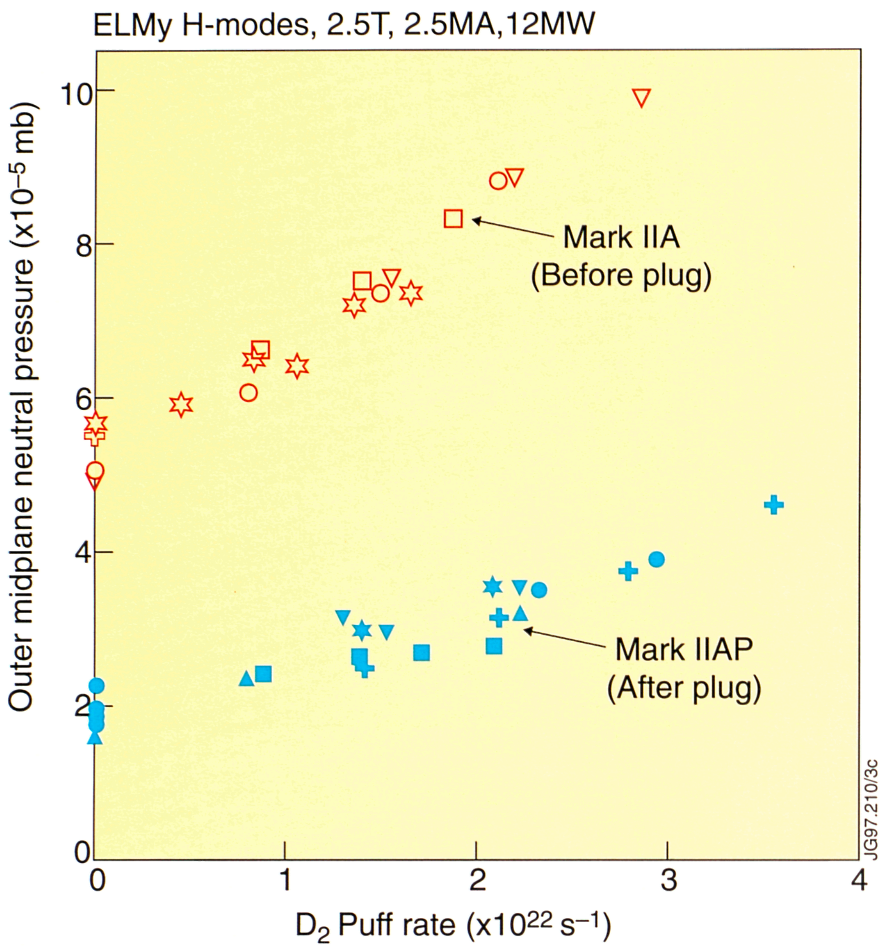


Fig.21: Further closure of the bypass leaks reduced the mid-plane neutral pressures

The frequency of certain plasma instabilities, the Edge Localised Modes (ELMs), determined by plasma triangularity and gas puff strength, had a greater effect on performance than either target orientation or magnetic flux expansion in the divertor.

The further closure of the by-pass leakage paths in October 1996 resulted in a further reduction in neutral recycling in the main chamber, but did not significantly change plasma performance or purity (perhaps due to the increased carbon tile coverage of the inner wall). A comparison of the behaviour before and after plugging the bypass leakage paths showed that the midplane pressure was considerably reduced after plugging (Fig.21). It also showed that the confinement of the main plasma was correlated with the divertor neutral pressure, rather than the mid-plane neutral pressure which had previously been assumed.

Sawteeth

Perturbations on the q=1 magnetic surface can result in the formation of large fluctuations in the central temperature and density. These fluctuations have been termed 'sawteeth'. They are also associated with the expulsion of energetic ions from the central region of the plasma. Understanding this process is important as the alpha-particles produced from deuterium-tritium fusion reactions might be lost before they can produce any effective heating of the plasma.

Preparation of High Performance Scenarios for DTE-I

The preparation of scenarios for DTE-1 concentrated on three high performance regimes: the hot-ion ELM-free H-mode; the high current ELMy H-mode and the optimised magnetic shear regime. The first two, were well developed before the present campaign, and continued to make progress during 1996. The last regime has built on developments on DIII-D (General Atomics, USA), TFTR (PPPL, USA) and

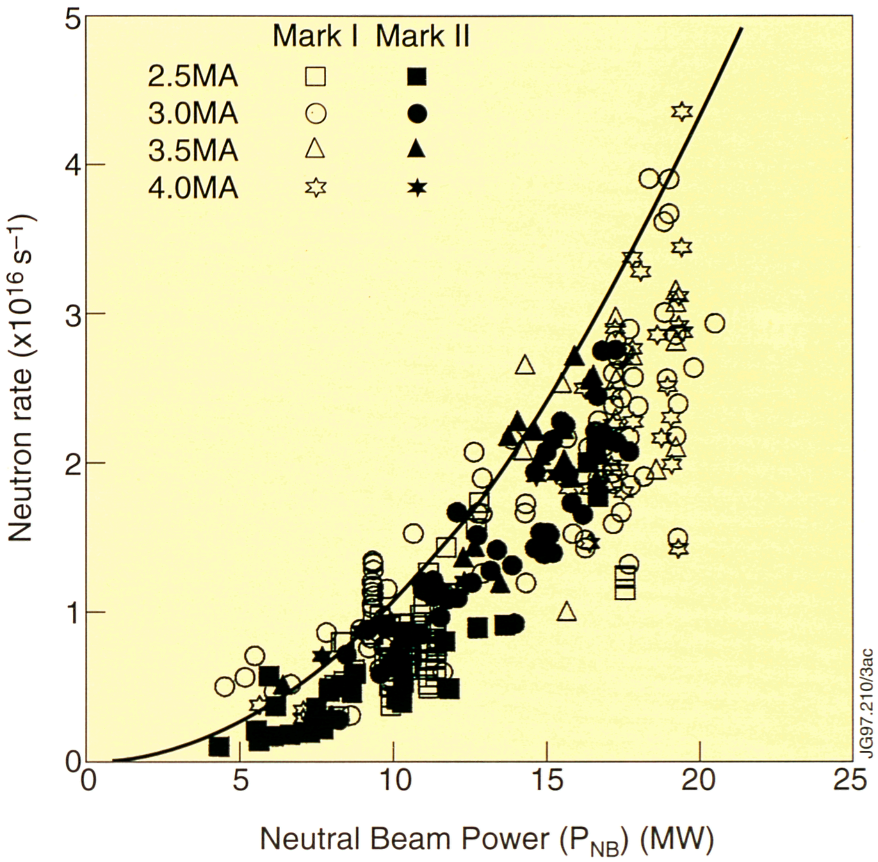


Fig.22: Neutron rate plotted versus total neutral beam power. (Open symbols refer to Mark I and closed symbols refer to Mark II)

JT-60U (JAERI, Japan) and has now achieved a fusion performance in deuterium equal to that of the hot-ion ELM-free H-mode during 1996. In spite of considerable progress, further work is still required to raise the operating density (to maximise the D-T fusion performance) and to improve discharge reliability. In the longer term, the optimised shear regime must demonstrate the steady-state capability for which it is of so much potential interest to reactor designers.

Disruptions

There is a maximum value of density which can be contained with a given plasma current. If this value is exceeded a disruption occurs when the plasma confinement is suddenly destroyed and the plasma current falls to zero in a short period of time. Under these conditions high mechanical and thermal stresses are produced on the machine structure. Disruptions are thought to be caused by instabilities mostly developing on the magnetic surface where q=2.

Hot-ion ELM-free H-modes

Hot-ion ELM-free H-modes, heated by high power neutral beam injection and augmented by ICRF heating, have produced high fusion yields and will form a cornerstone of DTE-1 in 1997. Strong pumping with the Mark IIA divertor has reduced the need for extensive conditioning for access to this regime, but has not improved confinement or performance significantly. The improved design of the pumped divertor target has eliminated the carbon "bloom", but MHD instabilities and a loss of confinement in the plasma core remain and ultimately limit performance and reproducibility.

Fusion performance in hot-ion ELM-free H-modes is similar with the Mark I and Mark IIA divertors. The same strong dependence on neutral beam heating power is seen, but neutron rates were restricted during 1996 to less than $3x10^6$ neutrons per second by the available beam heating power (~17MW) (Fig.22). Typical traces from a hot-ion H-mode plasma are shown in Fig.23. Improved performance has

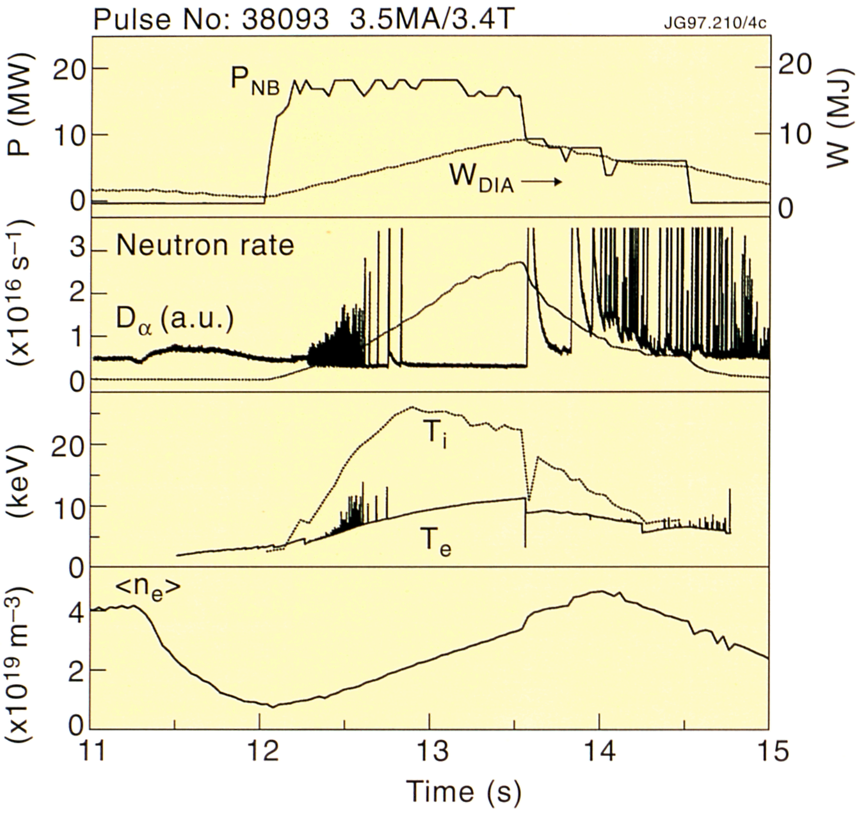


Fig.23: Typical time traces for a hot-ion plasma showing the time variation of neutral beam power, P_{NB}, stored energy, W_{DIA}, D-D neutron rate, D_α radiation, ion and electron temperatures (T_i and T_e) and volume averaged density $<n_e>$

been demonstrated when ICRF is combined with NB heating. Up to 9.5MW of ICRF power has been coupled and, together with beam heating, 25MW of additional heating power has raised the stored plasma energy up to 14MJ, with plasma currents up to 3.8MA.

Hot ion H-modes have produced the highest fusion yields in JET and will play an important role in future D-T experiments. The high yield phase is transient and is terminated, usually irreversibly, by a deterioration of confinement associated with a variety of magnetohydrodynamic (MHD) activity. The connection between MHD activity and confinement deterioration is not entirely clear. The irreversibility is due to a combination of confinement degradation and density increase, which reduces central power deposition by neutral beams and couples the ion and electron temperatures.

In general, three classes of MHD phenomena were involved in setting the limit to the high performance: sawteeth and other internal MHD instabilities occurred in the plasma centre; low frequency modes occurred in the outer 20% of the plasma radius; and "giant" ELMs occurred in the very edge of the plasma. The so-called outer modes have been identified as saturated low number external kink modes. "Giant" ELMs occur when the plasma is calculated to be unstable against kinks and ballooning modes simultaneously. Outer modes are observed as precursors to many ELMs.

The most likely mechanism to connect the MHD instability with the loss of confinement is that which connects core transport with edge plasma conditions. Models based on this idea account for a range of phenomena observed in tokamaks.

Density Control

Increasing the density can be achieved by introducing additional gas into the vacuum vessel, by the injection of energetic neutral atoms (neutral beam heating) and by solid pellet injection.

Increasing the input power to the plasma through additional heating raises the electron density limit. However, problems can occur when this heating power is switched off, if the electron density is too high. To overcome this problem, the plasma is moved, prior to the switch-off point, so that it bears on the carbon tiles covering the inner wall. The tiles have been found, to provide a pumping mechanism for removing particles so that the density can be reduced below the critical limit.

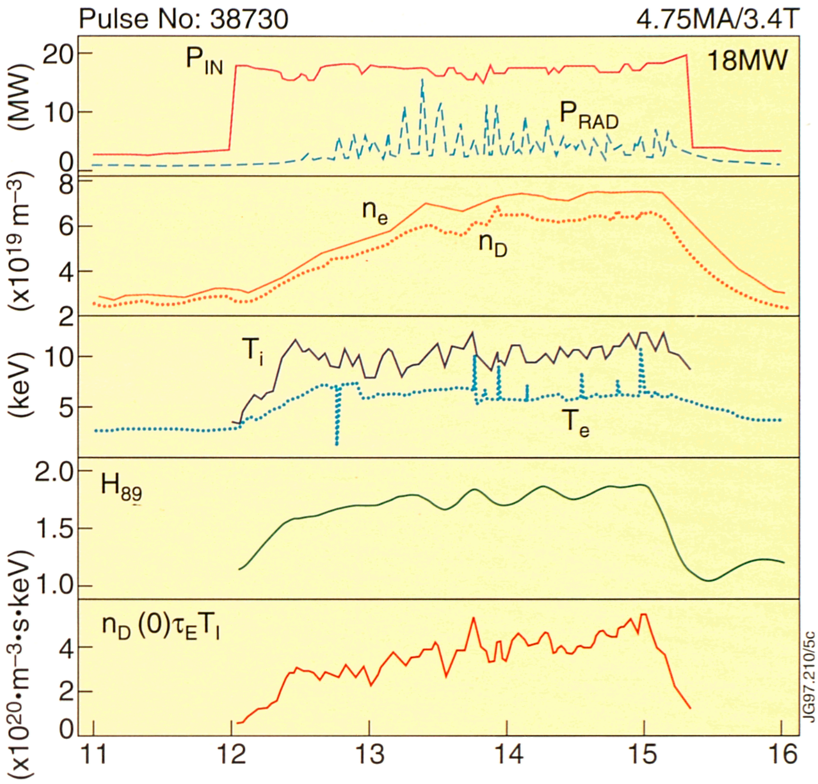


Fig.24: Time evolution of a steady-state ELMy H-mode at high current

If the MHD instability triggers the termination of the high performance phase, it should be possible to improve the fusion yield of these plasmas. Various amelioration techniques are being investigated.

High Current ELMy H-mode Operation

The JET tokamak, due to its large size and similar shape, is in a position to produce plasmas which most closely resemble those required for ITER. The confinement and fusion performance of steady state ELMy plasmas have been studied at plasma currents up to 5MA. A steady-state equivalent fusion power of ~3.5MW has been produced at 4.7MA with 17MW (Fig.24) of NB heating and at 3.5MA with 24MW of combined heating (16MW NB and 8MW ICRF). At 2.5MA, an ELMy H-mode can be maintained for the whole of the heating pulse (~10s) but above a current of ~3.5MA, most discharges suffer a spontaneous H-L back transition where the stored plasma energy begins to fall (and sometimes recovers, with up to three cycles) before the end of the high power phase (Fig.25).

Plasma Beta

The economic efficiency of a tokamak reactor is determined, partly, by the maximum plasma pressure which can be contained by the magnetic fields in the device. In particular, the important parameter is the plasma beta β_T, defined as the ratio of plasma pressure to the pressure of the confining magnetic field (β_T is proportional to nT/B_T^2, where n is the plasma density, T the plasma temperature and B_T the toroidal magnetic field). This limit expected theoretically, is the so-called Troyon limit $\beta_T(\%)=2.8I_p(MA)/B_T(T)a(m)$, where I_p is the plasma current and a is the minor radius.

Optimised Shear Modes of Operation

Current profile control has proved to be an important technique for optimising confinement in tokamaks. Of particular significance during 1996 was the development of the high performance optimised shear plasmas. Following JET's pioneering work in achieving enhanced performance with deep pellet fuelling to reverse the magnetic

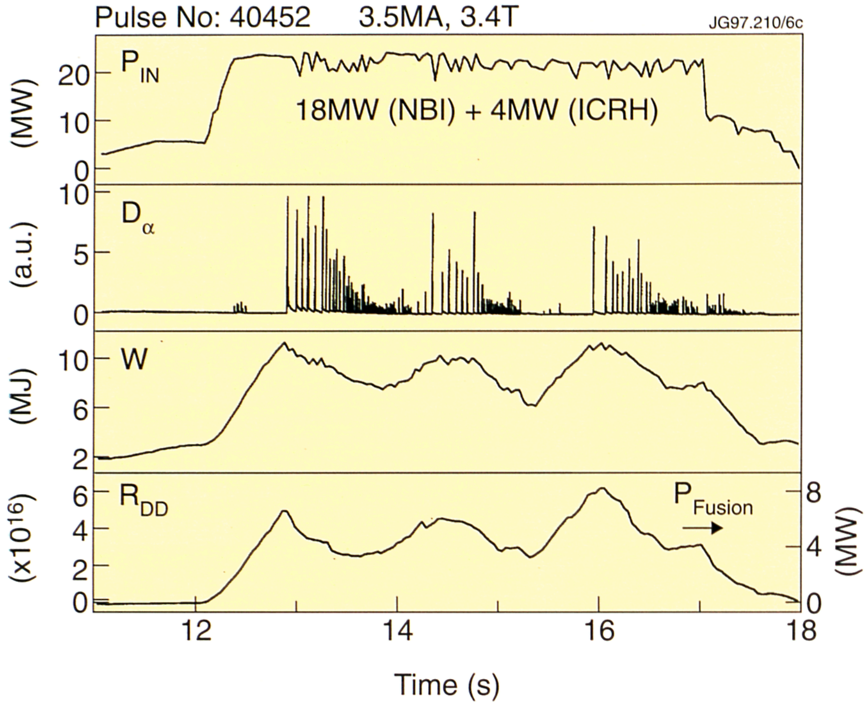


Fig.25: Time evolution of a steady state ELMy H-mode at 3.5MA plasma current, showing relaxation of stored energy (and fusion power)

shear in the central plasma, and building on the results obtained recently in DIII-D, TFTR and JT-60U, proper control of the current rise and power waveforms has resulted, for power levels above ~17MW, in the formation of an internal transport barrier (which expands to about half the plasma radius) and high fusion performance. In JET, the core transport is reduced when the main power waveform is applied during the current ramp phase of the plasma, with or without a preheating phase. The main evidence of an internal barrier can be seen from the ion temperature profile, as shown in Fig.26.

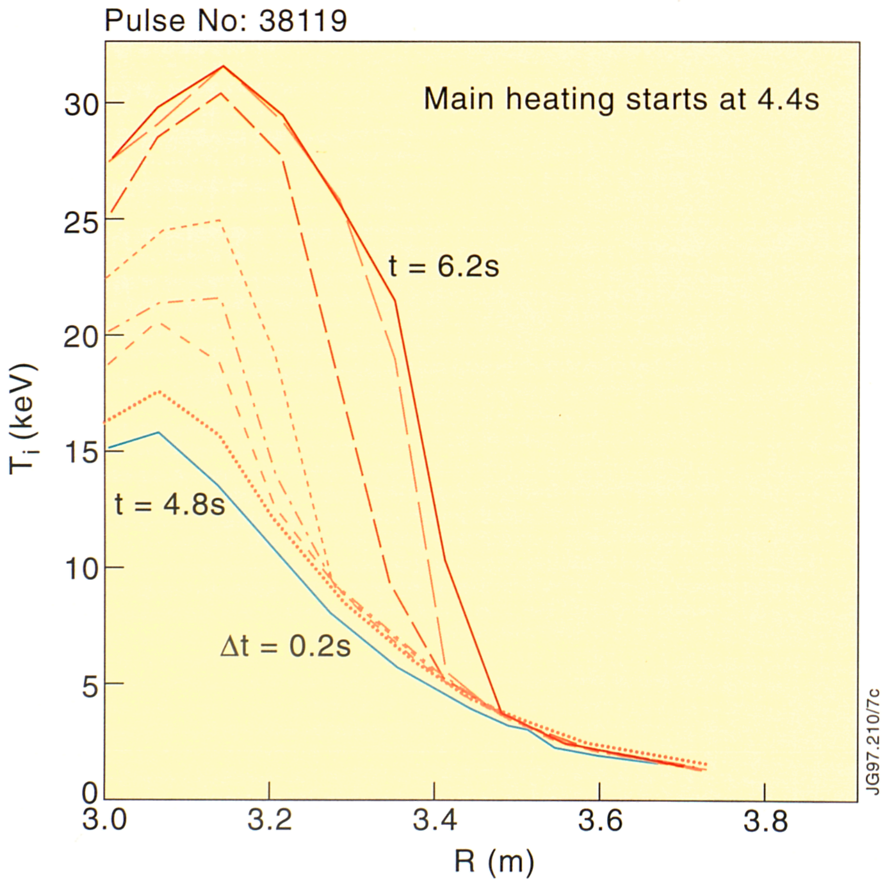


Fig.26: Ion temperature profiles from charge exchange recombination (B_t=3.4T, 2.5<I_p<3MA) with early power waveform and 1MW (ICRF) of preheating showing an internal transport barrier

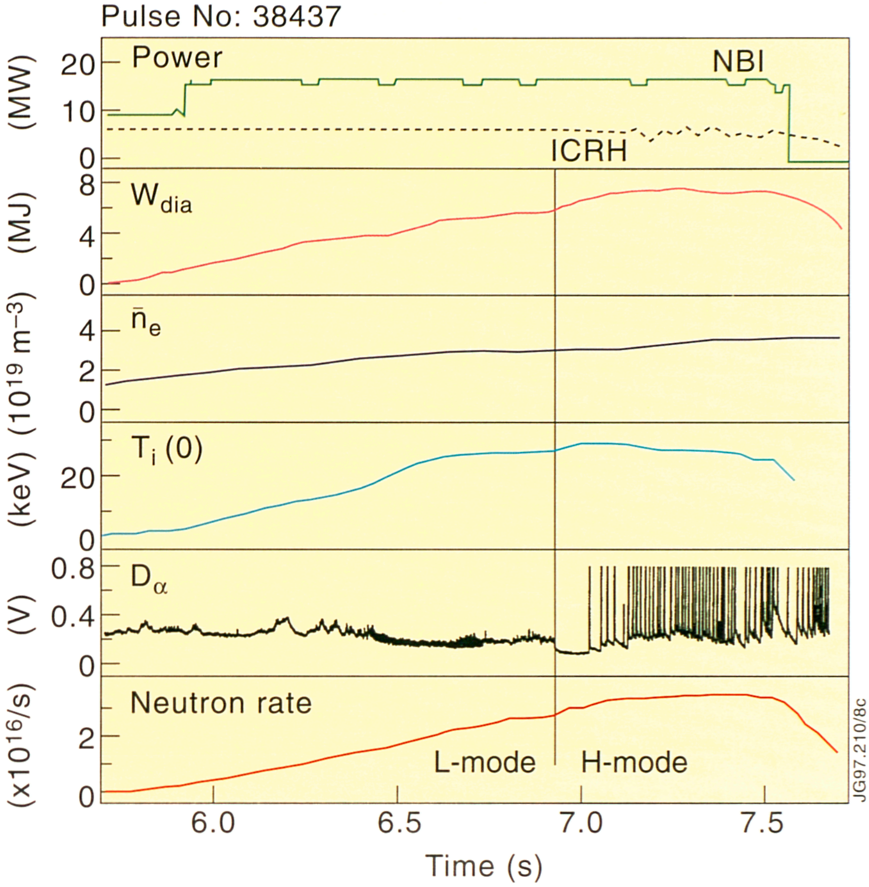


Fig.27: Time history of a high fusion yield pulse with shear optimisation (B_t=3.4T, 2.5<I_p<3MA)

Under these conditions, high confinement L-modes (H_{89}~2) with simultaneously high ion (32keV) and electron (15keV) temperatures and high neutron rates (3.9x10^{16} neutrons per second, 80% computed to be thermal in origin) have been produced with up to 28MW of combined NB and ICRF power for longer than an energy confinement time (0.4s). There is no apparent accumulation of impurities (Z_{eff} remains constant at ~1.7) and the ratio of neutron yield to stored plasma energy is high. A typical example of time traces obtained is shown in Fig.27. Fusion performance is already comparable to that achieved in the best hot ion ELM-free H-modes of 1996 and there is promise for further improvement, but the diagnostic capability for measuring the current profile is a limiting factor.

MARFE

A MARFE (Multifaceted Asymmetric Radiation From the Edge) is a toroidally symmetric band of cold, highly radiating plasma which normally forms at the plasma inner wall. It can occur when the plasma edge density is high and results from of an imbalance between the power flowing along magnetic field lines in the edge and the power lost locally due to radiation. A MARFE grows rapidly, on a timescale of ≈10-100 milliseconds, but it can persist for several seconds. In some cases, the MARFE leads to a disruption, but in others the main consequence is a reduction in the edge density.

Alfvén Eigenmode Experiments

Toroidicity-induced Alfvén Eigenmodes (TAEs) can be driven unstable by fast particles originating from neutral beam injection, ICRF heating or fusion reactions. Destabilisation of such modes in reactors is a subject of concern as these may lead to anomalouly rapid losses of energetic alpha-particles, reducing alpha-particle heating efficiency and potentially damaging the first wall. These modes are characterised by high frequency (typically 100-200kHz in JET), which depends on the Alfvén speed.

Systematic studies of weakly damped Alfven eigenmodes have concentrated on the three issues of mode stability, direct observation of fast particle drive in high performance plasmas and the effects of relatively large amplitude Alfven eigenmodes on fast particle orbits. Both the saddle coils and the non-linear interaction of two fast waves in the ICRF range of frequencies have been used. A novel technique based on real-time mode detection and digital control of the frequency allows the exciter frequency to be locked to the mode frequency. A small sweep of a few kHz superimposed enables the damping rate also to be determined. This technique has been proven with NB injection and will be used during DTE-1 to measure the intrinsic excitation by alpha-particles. Furthermore, magnetic fluctuations, identified as toroidal Alfven eigenmodes, have often been observed during performance limitations ascribed to outer modes. However, agreement between experimental and simulated neutron yields can be obtained even when toroidal Alfven eigenmodes are expected to be present.

Physics Studies for ITER

ITER-relevant Scaling Studies

The plasma cross-section envisaged for ITER shows a strong resemblance to the geometries that can be produced in JET and DIII-D (General Atomics, USA). Therefore, it is possible to carry out experiments on both JET and DIII-D in which dimensionless parameters describing the plasma have the same values as intended for ITER. There may be 15-20 dimensionless parameters, but only a few are found to have an impact on confinement. The variables are:

a) Normalised collisionality, υ^*;

b) Plasma beta, β;

c) Shape parameters like elongation, and triangularity;

d) Safety factor, q, and aspect ratio;

e) Normalised Larmor radius ρ^*;

The only difference between ITER, JET and DIII-D lies in ρ^*. (Here $\rho^*=\rho_i/L$, where L is the machine scale-length and ρ_i is the Larmor radius, which is the radius of the plasma ions motion gyrating in the magnetic field, B). Therefore, the variation of confinement scaling with ρ^* is crucially important to predictions of ITER's performance. Such predictions must include (i) L-mode confinement; (ii) the threshold power and density values needed to obtain an H-mode; and, (iii) H-mode confinement scaling.

The threshold power for access to the H-mode has not changed substantially since the introduction of the pumped divertor (Fig.28). It is independent of the magnetic configuration and the type of additional heating (neutral beam or ICRF)

Impurities

Impurities released from interactions between the plasma and material surfaces can have major effects on plasma behaviour by causing:

(a) increased radiation losses;

(b) dilution of the number of ions available in the plasma between which fusion reactions can occur.

*A measure of the overall impurity level is given by Z_{eff} which is defined as the **average** charge carried by the nuclei in the plasma. A pure hydrogen plasma would have $Z_{eff}=1$ and any impurities in the plasma would cause this value to be increased. In JET, Z_{eff} is generally in the range from 1.2-3.*

Major energy losses can result from two radiation processes:

- *Bremsstrahlung Radiation - radiation is emitted when electrons are decelerated in the electric field of an ion. The amount of radiation emitted increases with Z_{eff}. Bremsstrahlung radiation imposes a fundamental limit to the minimum plasma temperature that must be attained in a fusion reactor;*
- *Line Radiation - heavy impurities will not be fully ionised even in the centre of the plasma and energy can therefore be lost through line radiation.*

Considerable effort is made to keep the level of impurities in the JET plasma to a minimum. The vacuum vessel is baked at 300°C to remove gas particles trapped on the vessel walls which might be released by plasma bombardment.

Interactions between the plasma and vacuum vessel walls would result in the release of heavy metal impurities. To reduce this possibility, the edge of the plasma is defined by upper and lower belt limiters. These are cooled structures circling the outboard torus wall with carbon or beryllium tiles attached. Carbon and beryllium have a relatively low electric charge on the nucleus.

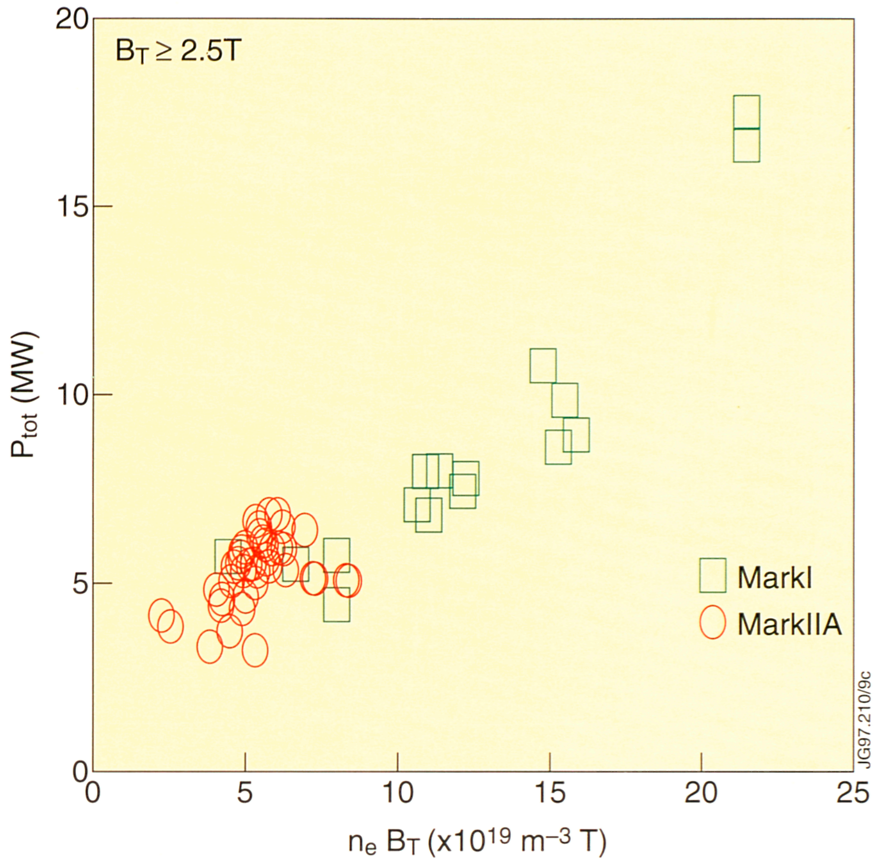


Fig.28: Threshold power for H-mode in both Mark I and Mark IIA divertor configurations

Energy Confinement

Energy confinement in tokamaks when the plasma is bounded by a material limiter generally degrades as the input power to the plasma increases. The result is that the energy confinement time, τ_E, falls approximately as the square root of the input power. This regime is said to exhibit L(low)-mode confinement. In plasmas with a magnetic limiter (that is with an internal magnetic separatrix or X-point), a transition can occur above a certain threshold input power to a regime in which the energy confinement time is increased by a factor of two or more greater than in the L-mode situation. This has been called H(high)-mode confinement. However, a similar degradation with input power is observed.

In addition to the improved energy confinement time, enhanced particle confinement is observed and the temperature and density close to the separatrix can increase substantially, resulting in the formation of plasma profiles with an edge 'pedestal'. The precise conditions for the transition into the H-mode vary with plasma parameters. For example, the threshold power for the transition increases at least linearly with the toroidal magnetic field. In recent years, the H-mode transition has also been observed in plasmas with a material limiter, although the power threshold is usually significantly higher than in magnetic limiter (X-point) plasmas.

and exhibits no hysterisis in either edge temperature or, probably, heating power. The data follows quite well the global scaling expressions derived from a multi-machine threshold data base, although a deviation from the linear density scaling is evident at densities above $5x10^{19}m^{-3}$.

In conjunction with DIII-D, confinement in the plasma core of ELMy H-mode discharges with ITER dimensionless parameters has been shown to depend on the three dimensionless parameters: normalised Larmor radius, ρ^*, collisionality, υ^* and plasma pressure, β. Similarity experiments with DIII-D and C-Mod have validated the approach. Precise experiments on JET have shown that confinement is close to a gyro-Bohm scaling. The results were compared with the ITERH93-P scaling expression, which can be written in dimensionless form as follows:

$$\beta\tau_{TH} \propto \rho^{*-2.7}\ \upsilon^{*-0.28}\ \beta^{-1.2}$$

The ρ^* and υ^* dependencies confirmed the ITERH93-P scaling law used at present to predict the ITER confinement time (Fig.29). However, a very weak but favourable dependence on β is found, in contrast to the strong and unfavourable scaling with β of the ITERH93-P scaling.

The effect of different types of ELMs on confinement in high power, long pulse quasi-steady H-mode discharges has also been studied. Type III ELMs (conditions close to the L-H threshold) are found to be significantly worse for confinement than Type I "Giant" ELMs (conditions well above the L-H threshold). Specifically, with

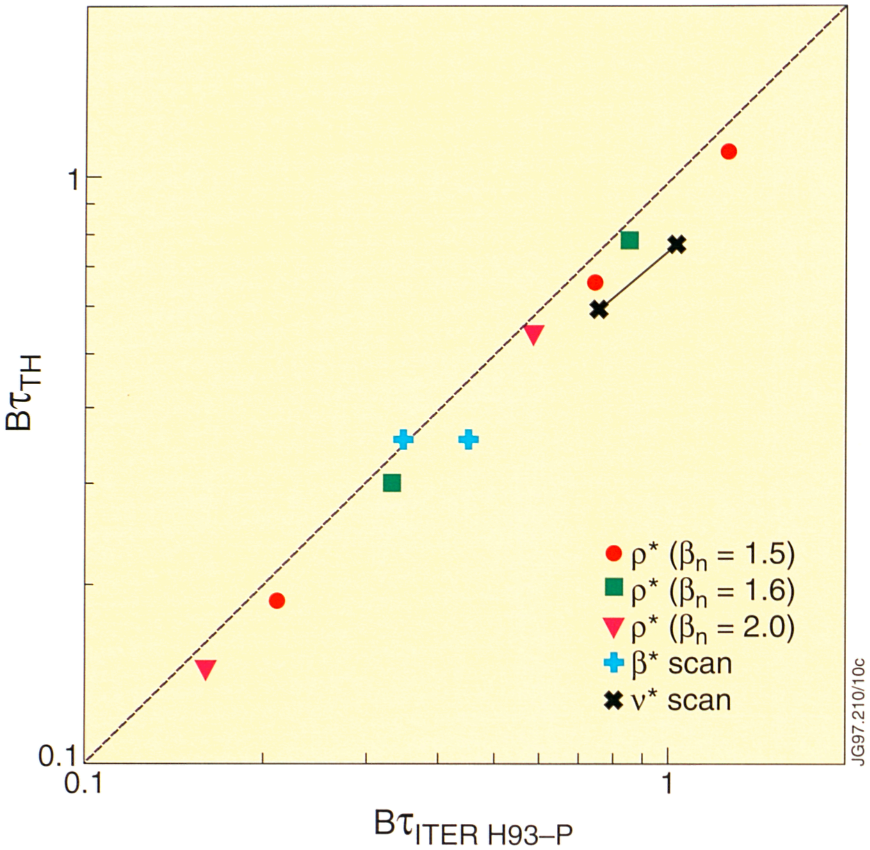


Fig.29: The normalised confinement time $B\tau_{TH}$ versus $B\tau_{ITERH93P}$

increasing radiated power to reduce the heat load to the divertor target plates, Type III ELMs are produced and confinement degrades progressively, no longer following the ITERH93-P scaling law. Thus, it is clear that somewhat better confinement will be required for ITER operations with a high radiated power fraction.

Preparation of an Integrated Operating Scenario for ITER

JET has studied the effect of increased divertor closure on the establishment of long pulse quasi-steady H-mode discharges with sufficiently high confinement for ignition in ITER and with edge conditions which allows sufficiently good energy and particle exhaust and low erosion (even with ELMs) for reasonably long component lifetimes.

Type I ELMy H-modes at high density have sufficient confinement, and Z_{eff} from intrinsic impurities is quite low and well within ITER requirements. However, Type I ELMs deposit high powers repetitively on divertor components and the scrape-off layer plasma density is low between ELMs. When extrapolated to ITER, operation with such ELMs would result in unacceptable heating and erosion of the target plates. However, with ICRF rather than neutral beam heating, the ELMs are much more frequent and have a lower amplitude, but this may be due to the lower particle and momentum sources associated with ICRF heating.

In Type III ELMy H-modes, the maximum radiated power fraction decreases with increasing divertor closure, from 80% with Mark I to 60% with Mark IIA after plugging the divertor by-pass leakage paths. Even so, the total power flow to the targets remains small since charge-exchanged neutral losses from the divertor appear to be higher with the more closed geometries. Plasma purity in such radiative discharges in Mark IIA has been found to fit the empirical scaling law between radiated power loss and Z_{eff} in the plasma core which was established from a multi-machine database. This scaling shows that impurity control will have to be slightly better for ITER operations with radiative plasmas. On the other

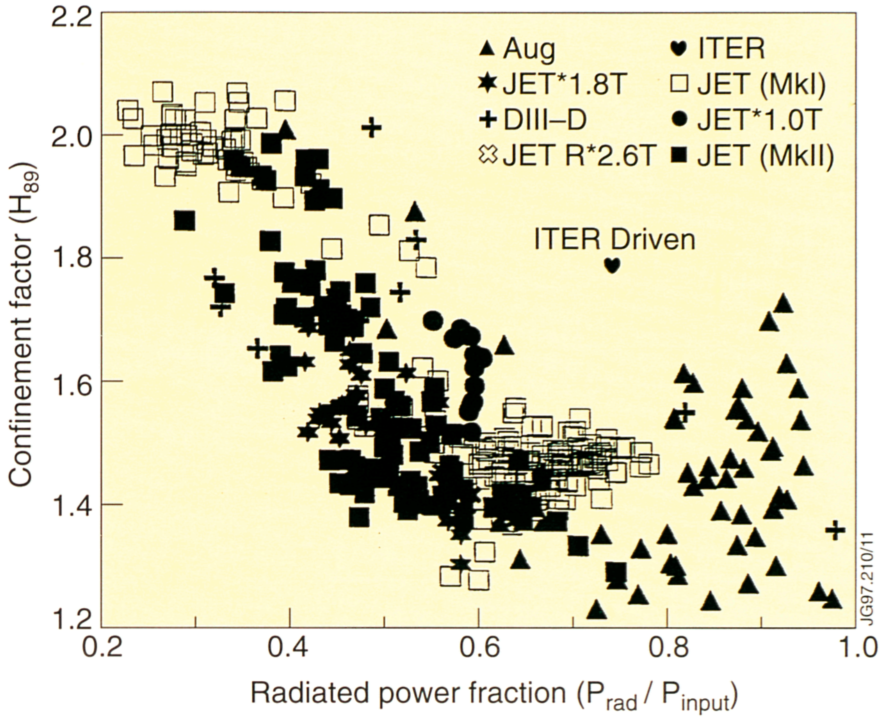


Fig.30: Confinement factor as a function of radiated power fraction

hand, confinement deteriorates with increasing radiated power fraction (Fig.30) and the scaling becomes less favourable than the gyro-Bohm scaling of ITERH93-P.

It is clear that further development is needed if ITER is to use either of these modes of operation.

Multi-Machine Database Collaboration

JET is making a significant contribution to the ITER multi-machine databases. The ITER Confinement Database and Modelling Expert Group is now responsible for the ITER L-mode Database, the ITER H-mode Database, the ITER H-mode Threshold Database and the ITER Profile Database. The official Expert Group (three members from each of the three ITER Parties) acts as a Steering Committee for the activities, whereas the actual Working Group is much larger. All participating tokamak groups, (i.e. ASDEX, ASDEX Upgrade, C-MOD, COMPASS-D, DIII, DIII-D, FTU, JET, JFT-2M, JT-60, JT-60U, PBX-M, PDX, RTP, START, TCV, TDEV, TORE SUPRA, TEXTOR, TFTR and T-10) are represented in the Working Group.

The current version of the L-mode database consists of data from 14 tokamaks: ASDEX, C-MOD, DIII, DIII-D, FTU, JET, JFT-2M, JT-60, PBX-M, PDX, TEXTOR, TFTR, TORE SUPRA AND T-10. The thermal L-mode confinement scaling determined from this database is:

$$\tau_{th}=0.023x\ I^{0.96}\,B^{0.03}\,R^{1.83}\,\varepsilon^{-0.06}\,\kappa^{0.64}\,n^{0.40}\,M^{0.74}\,\rho^{-0.73}$$

in units of MA, T, m, $10^{19}m^{-3}$, AMU and MW. This scaling can also be written in terms of dimensionless parameters as:

$$B\tau \propto \rho^{*-1.98}\,\nu^{*0.19}\,\beta^{-1.39}\,\varepsilon^{-4.26}\,\kappa^{0.87}\,M^{0.74}\,q^{0.14}$$

which corresponds to a Bohm scaling. Comparisons with the data in the ITER H-mode database show that the H-mode enhancement factor, defined by the thermal L-mode scaling, increases with machine size (decreasing ρ^*) for both the ELM-free and ELMy H-mode data, see (Fig.31(a) and (b)). The total confinement scaling determined from this database is very close to the ITER89-P scaling.

The H-mode database consists of data from six Tokamaks: ASDEX, DIII-D, JET, JFT-2M, PBX-M and PDX. The thermal ELM-free H-mode confinement scaling, determined from this database, is ITERH93-P. The current ELM classification in

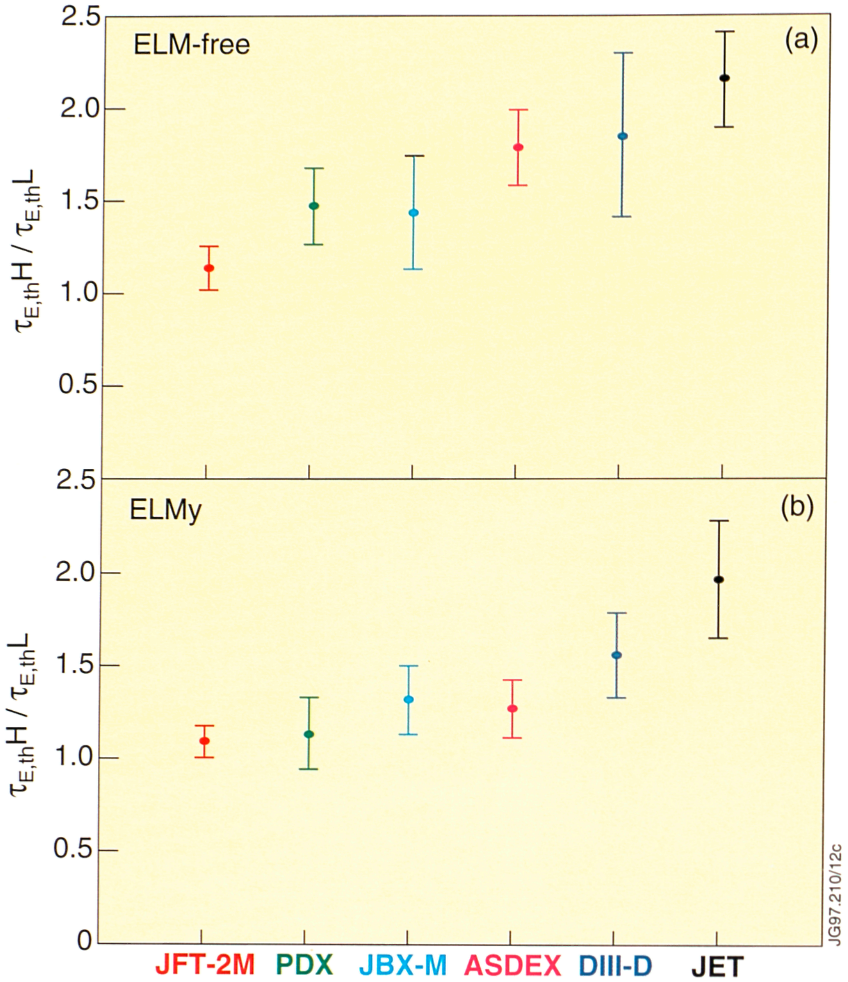


Fig.31: (a) Ratios of the ELM-free H-mode thermal confinement time to the L-mode scaling; (b) Ratios of the ELMy H-mode thermal confinement time to the L-mode scaling for a series of tokamaks

the database does not allow for a determination of scalings for the various types of ELMs. The thermal ELMy H-mode scaling, ITERH93-P (ELMy) is the best fit to the ELMy standard subset of this database. The assumption that Type I ELMs degrade the underlying ELM-free H-mode confinement by a constant fraction leads to the log-linear thermal Type I ELMy H-mode scaling 0.85xITERH93-P. Work has also started on the next version of the H-mode database, which will include new data from DIII-D, and JET and from ASDEX-Upgrade, C-MOD, COMPASS-D, JT-60U, TCV and TEXTOR.

Progress Towards a Reactor

To improve the fusion performance of JET, two main approaches have been exploited during 1996. These are the conventional hot-ion H-mode and the optimised shear hot-ion L-mode.

In the case of the hot-ion H-mode, the main progress has been on the understanding and delaying of the MHD event called the outer mode. This has been identified as an external kink mode and it is found that by ramping the current downwards during the pulse its onset can be delayed. Other MHD events such as ELMs and sawteeth still limit the fusion performance of this mode of operation. However, the D-D performance has been slightly improved, with a neutron yield of 5.03×10^{16} neutrons per second, being achieved by the addition of ~2MW of ICRF power to the 18MW of neutral beam heating. It is expected that with a 50:50 D-T mix, approximately 12MW of fusion power should be produced, in the DTE-1 experiments in this mode of operation.

In preparation for the D-T programme, during 1997, a low power hot-ion scenario has also been developed. It is expected that electron heating by the alpha-particles should be observable in this type of pulse.

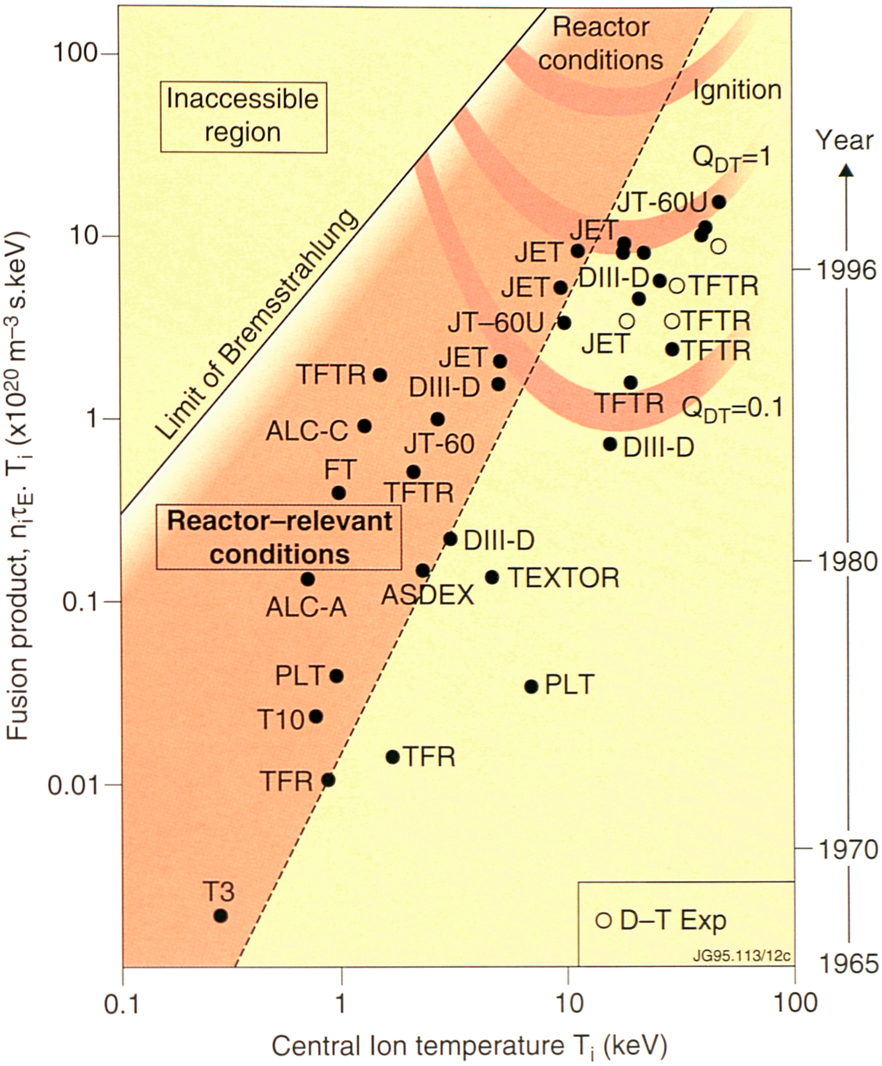


Fig.32: Triple fusion product as a function of ion temperature, T_i, for a number of tokamaks world-wide

Rapid progress has been made during 1996 on the development of the hot-ion optimised shear scenario. In this scenario, the plasma is kept in the L-mode regime with the central safety factor well above unity. The shape of the current profile being adjusted by using both lower hybrid and ICRF heating. A large region (r/a<0.55) of improved central confinement has been obtained and as a result strongly peaked density and temperature profiles have been obtained. The peak D-D fusion performance of this type of pulse is slightly better than that of the conventional hot-ion H-mode at 5.6×10^{16} neutrons per second and its duration is about double that of the hot-ion H-mode. It is expected that this type of operation should give a fusion power output in D-T of about 13MW for 21MW of input power. The present intention is to exploit both types of operation in the DTE-1 experiments.

Further progress has also been made on the other large experiments TFTR, DIII-D and JT-60U using the optimised shear approach. Perhaps the most notable achievement is an equivalent Q_{DT} of unity obtained in JT-60U.

The fusion triple product values of the high performance pulses in both impure deuterium and in the D-T pulses for JET and TFTR are compared in Fig.32 with the latest results from the other machines world-wide to illustrate the progress that has been made over the last 30 years.

Future Programme

Introduction

In 1978, the original objectives of JET were set out in the JET Design Proposal, EUR-JET-R5, as follows:

'The essential objective of JET is to obtain and study a plasma in conditions and dimensions approaching those needed in a thermonuclear reactor. These studies will be aimed at defining the parameters, the size and the working conditions of a Tokamak reactor. The realisation of this objective involves four main areas of work:

i) the scaling of plasma behaviour as parameters approach the reactor range;

ii) the plasma-wall interaction in these conditions;

iii) the study of plasma heating; and

iv) the study of alpha-particle production, confinement and consequent plasma heating.

The problems of plasma-wall interaction and of heating the plasma must, in any case, be solved in order to approach the conditions of interest.

An important part of the experimental programme will be to use JET to extend to a reactor-like plasma, results obtained and innovations made in smaller apparatus as a part of the general tokamak programme. These would include: various additional heating methods, first wall materials, the control of the plasma profiles and plasma formation.

Objectives of JET

The essential objective of JET is to obtain and study plasma in conditions and with dimensions approaching those needed in a thermonuclear reactor. These studies will be aimed at:

1. Scaling of plasma behaviour as parameters approach the reactor range;

2. Plasma-wall interactions in these conditions;

3. Plasma heating; and

4. Alpha-particle production, confinement and consequent plasma heating.

At the start of 1996, JET had entered the ITER-EDA Support Phase of its ITER Support Programme, and started the year in shutdown for installation of the Mark II support structure. This will be the basis for all future divertor work at JET and is the key to the programme to 1999. In addition, the "more-closed" Mark IIA divertor target assembly was installed. During the shutdown, work was also undertaken on various systems in preparation for the next period of D-T operation (DTE-1), scheduled for Summer 1997, and for the Remote Tile Exchange shutdown after DTE-1. The 1996 campaign concentrated on specific ITER-relevant issues related to the Mark IIA divertor and, due to their importance for predicting ITER's ignition margin and fusion power output, the scaling of the H-mode threshold power and energy confinement.In addition, preparation of high performance scenarios for DTE-1 was a high priority of the campaign.

Since the beginning of its experimental campaign, extensive studies had been made in the first and third areas of work of JET's objectives: reactor relevant temperatures (up to 30 keV), densities (up to 4 x $10^{20}m^{-3}$) and energy confinement times (up to 1.7s) had been achieved in separate discharges. The second area of work had been well covered in the limiter configuration for which JET was originally designed. However, the highest performance JET discharges had been obtained with a 'magnetic limiter', (or X-point configuration). The duration of the high performance phase of these discharges exceeded 1.5s; this was achieved by careful design of the targets and specific operation techniques, but is limited, ultimately, by an unacceptably high influx of impurities, characterized by a rapid increase in electron density, effective ionic discharge and radiated power (referred to as the 'bloom').

The fourth area of work had been started by earlier studies of energetic particles produced as fusion products or by ion cyclotron resonance heating (ICRH). It was addressed further during 1991 by the first tokamak plasma experiments in deuterium-tritium mixtures. The high performance achieved in deuterium discharges, together with the experience gained in making substantial modifications to JET in a beryllium environment and with significant vessel activation, gave confidence that an experiment with about 10% tritium in the plasma could be performed and would provide data that could be used to plan an effective campaign of deuterium-tritium experiments in 1996.

During 1991, the JET Council had approved the policy of a step-wise approach to introduction of tritium in advance of the full D-T phase of operations. As a first step, JET successfully carried out the preliminary tritium experiment (PTE-1) in 1991. A release of fusion energy in the megawatt range in a controlled fusion device was achieved for the first time in the world.

In the 1991/92 campaign, JET achieved parameters approaching breakeven values for about a second, resulting in large bursts of neutrons. However, in spite of the pulse continuing for many seconds after reaching peak plasma values, the neutron count fell away rapidly as impurities entered the plasma and lowered its performance. This limitation on the time for which near-breakeven conditions could be maintained was due to the poisoning of the plasma by impurities (the 'bloom'). This further emphasised the need to provide a scheme of impurity control suitable for a Next Step device.

In late 1991, the Council of Ministers approved a prolongation of JET by four years until 31st December 1996. The extension allowed JET to implement the

Pumped Divertor Phase of operation, to establish effective control of plasma impurities in operating conditions close to those of the Next Step. This programme of studies is being pursued before the final phase of full D-T operations in JET.

During 1993, a large proportion of JETs effort was devoted to work for the pumped divertor phase of operations. Four divertor coils and casings were installed inside the vacuum vessel. The Pumped Divertor Characterisation Phase was undertaken during 1994. The plasma current was increased to 5MA, the total heating power to 26MW, the stored energy to 11.3MJ and the neutron rate to $4x10^{16}$ neutrons per second.

1994 saw significant progress in optimising peak fusion performance and extending operation to the reactor relevant steady-state ELMy H-mode, obtained under a variety of conditions. The high β_p regime was also extended to steady-state and to the reactor relevant domain. The high power handling capability of the Mark I divertor target was demonstrated and the severe impurity influxes (carbon "blooms"), which previously terminated high performance plasmas, were eliminated. The cryopump reduced recycling, eliminated the effects of wall saturation (observed in previous long pulse operation), allowed effective particle control, and allowed higher performance.

The 1995 programme addressed the central problems of the ITER divertor: efficient dissipation of the exhausted power, control of particle fluxes and effective impurity screening, using both carbon fibre composite and beryllium as the power handling material. The plasma current was increased to 6MA (a world record in an X-point configuration), the total heating power to 32MW, plasma stored energy to 13.5MJ (the highest energy recorded in a JET plasma) and the neutron rate to a new JET record in deuterium of $4.7x10^{16}$ neutrons per second. ITER-relevant quasi-steady state ELMy H-modes were also studied at high power, high current, high β and in combination with detached divertor plasmas and radiative power exhaust.

The campaign with CFC tiles on the first-wall was successfully completed in early-1995. This was followed by experiments to assess the performance of beryllium as a divertor target tile material and to compare it with CFC. In response to a request from the ITER Joint Central Team, beryllium melting was induced at ITER-relevant heat fluxes to see whether a protective radiative shield was established.

In 1996, the Mark IIA Pumped Divertor behaved as expected. It offered improved power handling over the Mark I divertor, pumped the plasma 2-3 times more rapidly and showed signs of increased neutral recycling in the divertor region. The latter feature showed up particularly well in the detachment of the divertor plasma from the target at significantly lower main plasma density than Mark I configuration, in agreement with code predictions. Closure of the divertor to reduce leakage of neutrals from the divertor to the main plasma proved to have little effect on plasma purity or performance. Initial results following the further closure of the bypass leaks did not lead to significant differences in plasma behaviour. On ITER-relevant scaling studies, the threshold power for the H-mode was independent of the type of heating (NB or ICRF), no hysterisis was found, but the data dispersion remained large. Steady-state ITER-like plasmas were achieved at high current and heating power and reached an equivalent Q_{DT}~0.3.

Overall, these achievements show that the main objectives of JET are being actively addressed and substantial progress is being made.

Future Plans

The JET Programme was divided into phases fitting within the accepted life time of the Project. Phase I (Ohmic Heating Studies) was completed in September 1984, and Phase II (Additional Heating Studies) in October 1988. Phase III (Full Power Optimization Studies) ended in February 1992. The scientific aims of Phase III were to obtain maximum performance in limiter configuration (currents up to 7MA) and to optimize X-point Operation (currents up to 6MA).

JET future plans are dominated by the insertion of a new phase of the Project (Phase IV: Pumped Divertor Configuration and Next-Step Oriented Studies). This phase is subdivided into a Divertor Characterization Plasma and an ITER Support Phase. This new phase extended the lifetime of the Project up to the end of 1996.

The Pumped Divertor Characterisation Phase ended in June 1995. During this period, the Mark I pumped divertor was most effective and allowed a broad-based and highly ITER-relevant research programme to be pursued.

The Mark IIA divertor installation was completed byMarch 1996. During 1996, the Mark IIA Pumped Divertor was tested.

Preparations also continued on various systems in preparation for the next period of D-T operation (DTE1) scheduled for Summer 1997, and for the Remote Tile Exchange shutdown after DTE1.

Objectives in support of ITER

The extension of JET to the end of 1999 was officially approved in mid-1996. The purpose of the extension is to provide further data of direct relevance to ITER, especially for the ITER-EDA, before entering into a final phase of D-T operation. In particular, the extension:

i) will make essential contributions to the development and demonstration of a viable divertor concept for ITER; and
ii) carry out experiments using D-T plasmas in an ITER-like configuration, which will provide a firm basis for the D-T operation of ITER;

while allowing key ITER-relevant technology activities, such as the demonstration of remote handling and tritium handling, to be carried out.

Divertor Studies

The divertor must fulfil three main functions:

(i) exhaust plasma power at acceptable erosion rates;
(ii) control plasma purity; and
(iii) exhaust helium "ash" and provide density control. For ITER, successful divertor operation must also be compatible with high confinement (H-mode) operation with Edge Localised Modes (ELMs).

Erosion can be reduced by decreasing the plasma temperature at the target plates which can be achieved with high density and high recycling near the target plates. However, the exhausted plasma power conducted to the targets in this high recycling regime is not reduced and must be distributed over a large surface area. To some extent, this can be achieved by inclining the targets to project a larger surface area to the conducted heat flux which flows along the magnetic field.

An alternative approach is to reduce the conducted power to the targets by atomic physics processes (charge exchange, hydrogen and impurity radiation) in the divertor channel. These power losses can be enhanced by seeding the divertor plasma with impurities which must then be retained in the divertor by plasma flows. This requires sufficient pumping and recirculation of the plasma in the divertor. Of course, the divertor conditions must not affect adversely the main plasma performance and this requires that the divertor plasma must be decoupled as much as possible from the main plasma. In particular, the leakage of neutrals from the divertor to the main plasma must be reduced as far as possible. Such "closure" of the divertor can be achieved by introducing baffle structures at the entrance to the divertor or maintaining a sufficiently dense plasma to attenuate neutrals within the divertor (plasma "plugging"). The geometry of the divertor is thus important in providing the necessary degree of closure, and several different divertor configurations must be tested.

The JET divertor programme is based on three divertor configurations (Mark I, Mark IIA and an ITER-specific Mark IIGB), which it is planned to test sequentially in the period up to the middle of 1998 (end of the ITER-EDA). The relatively "open" Mark I divertor which was used for the 1994/95 Experimental Campaign was replaced during 1995/96 by the Mark II divertor, which comprises a common base structure capable of accepting various target assemblies. This allows the divertor geometry (degree of closure and target configuration) to be varied and its effect on divertor and main plasma performance to be studied.

Due to the need to test various divertor geometries for ITER, the Mark II divertor has been designed so that its target assembly can be exchanged by remote handling, but it does not lend itself to the use of active cooling.

The first target assembly (Mark IIA), being used for the 1996/97 experimental campaign, is a moderate "slot" divertor, significantly more closed than the Mark I divertor. Mark IIA allowed operation under a wide range of plasma configurations and conditions and makes high power, high current operation possible on both horizontal and vertical target plates.

The second target assembly (Mark IIGB) will be a deep divertor with a well baffled entrance. The aim of the Mark IIGB configuration is to distribute the exhaust power over the length of the divertor. This is assisted by free recirculation of neutrals below the baffle on one or both sides of the divertor plasma legs. Recirculation also allows greater flows, better pumping and better impurity retention in the divertor.

The various options for an ITER divertor will be studied in a timely and co-ordinated way by the investigation of these three generically different divertor configurations. This is designed to lead to a solution giving compatibility between power exhaust, purity control and high performance (H-mode). A major part of the strategy is the development and validation of numerical codes for the edge and divertor plasma so that they may be used for extrapolation to the geometry, dimensions and operating conditions of ITER. The experimental results from the three JET divertor configurations, together with those from smaller tokamaks and model calculations, will allow the ITER divertor design to be validated. This should be possible by the middle of 1998, in line with the ITER-EDA schedule.

D-T Plasma Studies

JET performed the first magnetic confinement experiments using a mixture of 10% tritium in deuterium in 1991. These produced significant fusion power (peaking at 1.7MW and averaging 1MW over 2 seconds). The US tokamak TFTR has since produced about 10MW of fusion power, using 50% tritium in deuterium, and has shown that, with their particular operating conditions and geometry, D-T plasmas have more favourable confinement properties than deuterium plasmas (isotopic effect). Two further periods of D-T operation (DTE-1 and DTE-2) are foreseen for the JET programme to the end of 1999.

The physics mission of DTE-1 will have as its main objective study of the isotopic effect on confinement scaling and H-mode threshold power in D-T plasmas. These will be the first experiments of this kind in the geometry appropriate to ITER and including a divertor, and will be essential to determine whether the D-T performance improvements observed in the circular cross-section TFTR tokamak are also realised in the D-shaped cross section of JET, and ITER. Furthermore, the H-mode threshold power in D-T plasmas will be determined for the first time in these experiments. This will allow more accurate assessments of the ignition margin and the heating requirements for ITER.

In addition, JET's capability for long pulse operation and impurity control should permit some 10MW of fusion power for several seconds (typically with 50% tritium). The alpha-particle heating will then make a significant contribution to the plasma power balance and this will allow the effects of alpha-particle heating (confinement and thermalisation of alpha-particles and stability of toroidal Alfven eigenmodes in the presence of alpha-particles) to be studied and experience gained for ITER. The operating conditions foreseen for ITER, namely long pulse ELMy H-mode plasmas, could also be studied in D-T, albeit at reduced levels of fusion power. These results could provide important information for the design of the ITER divertor.

As well as a physics mission, DTE-1 will also have a technology mission to carry out and demonstrate key ITER and reactor-relevant technologies, such as tritium handling and processing, remote handling and control, and heating systems operating in D-T. Specifically, DTE-1 will provide a first test of a large scale technology for processing tritium in an operating tokamak.

Operation in TFTR and detailed preparations for DTE-1 on JET have shown that a longer phase of D-T operation than DTE-1 is needed for a thorough study of the physics and technology of D-T plasmas. This is provided for by DTE-2, with substantial alpha-particle heating, capitalising on the performance improvements achieved in the preceding experimental campaigns with deuterium. This further period of D-T operation will also provide a full evaluation of the technology of processing tritium in support of an operating tokamak.

Programme Plan

The programme to the end of 1999 is illustrated in Fig.33. It covers all the agreed objectives for the JET extension. Its main aspects are summarised below.

The first period of D-T operation (DTE-1) is scheduled for Summer 1997, following an intervention to make the necessary final adjustments for D-T operations. The content and duration of DTE-1 has been defined to take account of the developing needs of ITER and the experience gained in JET and TFTR. The extent of DTE-1 is a compromise between studying essential D-T physics for the ITER-EDA and minimising the delays in the experimental programme that could result from certain component failures during DTE-1.

The physics mission of DTE-1 will last about four months and could produce up to $2x10^{20}$ neutrons. In this case, the activation of the JET vessel would prevent normal manned in-vessel intervention for up to one year after D-T operation. However, in-vessel components which are accessible could be repaired using the remote handling equipment developed for the Mark IIGB target assembly change. This equipment has demonstrated a very high level of reliability and is now fully proven for the planned remote handling tasks. Its versatility and ability to perform a wide variety of other tasks has also been demonstrated, provided access can be obtained. Normal manned access for ex-vessel repairs will be possible after DTE-1.

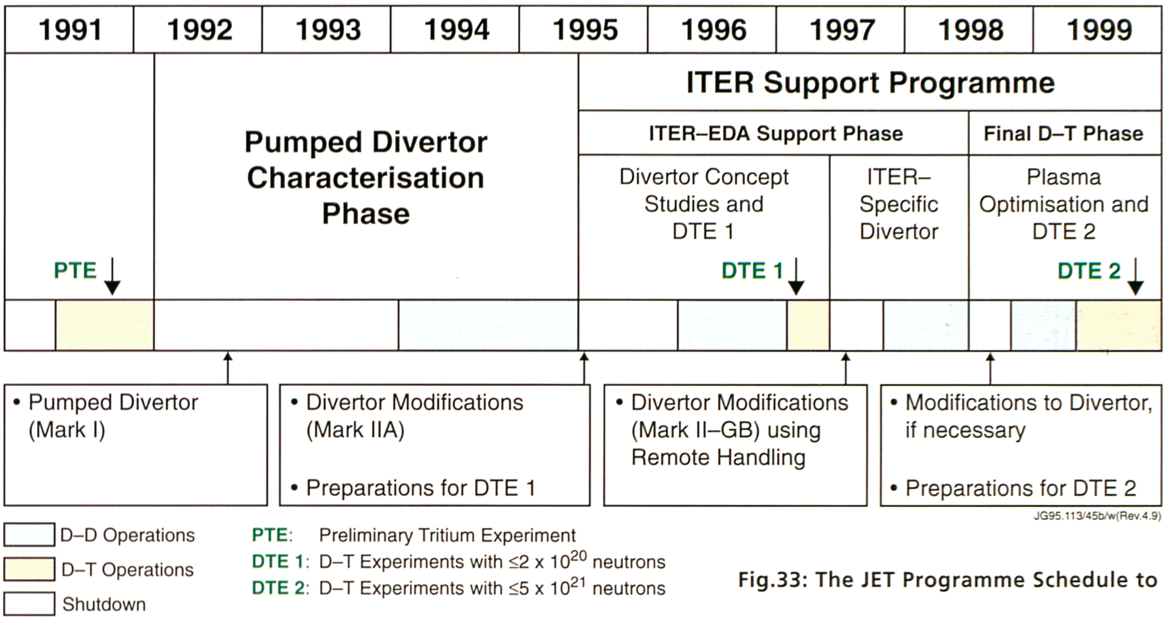


Fig.33: The JET Programme Schedule to 1999

In a five month shutdown planned to commence in June 1997, the Mark IIA target structure will be exchanged for a second target structure, the ITER-specific Gas-box divertor (Mark IIGB). The exchange will be made by remote handling without manned intervention. This remote handling operation will demonstrate, for the first time, one of the central technologies required both for ITER and for a fusion reactor.

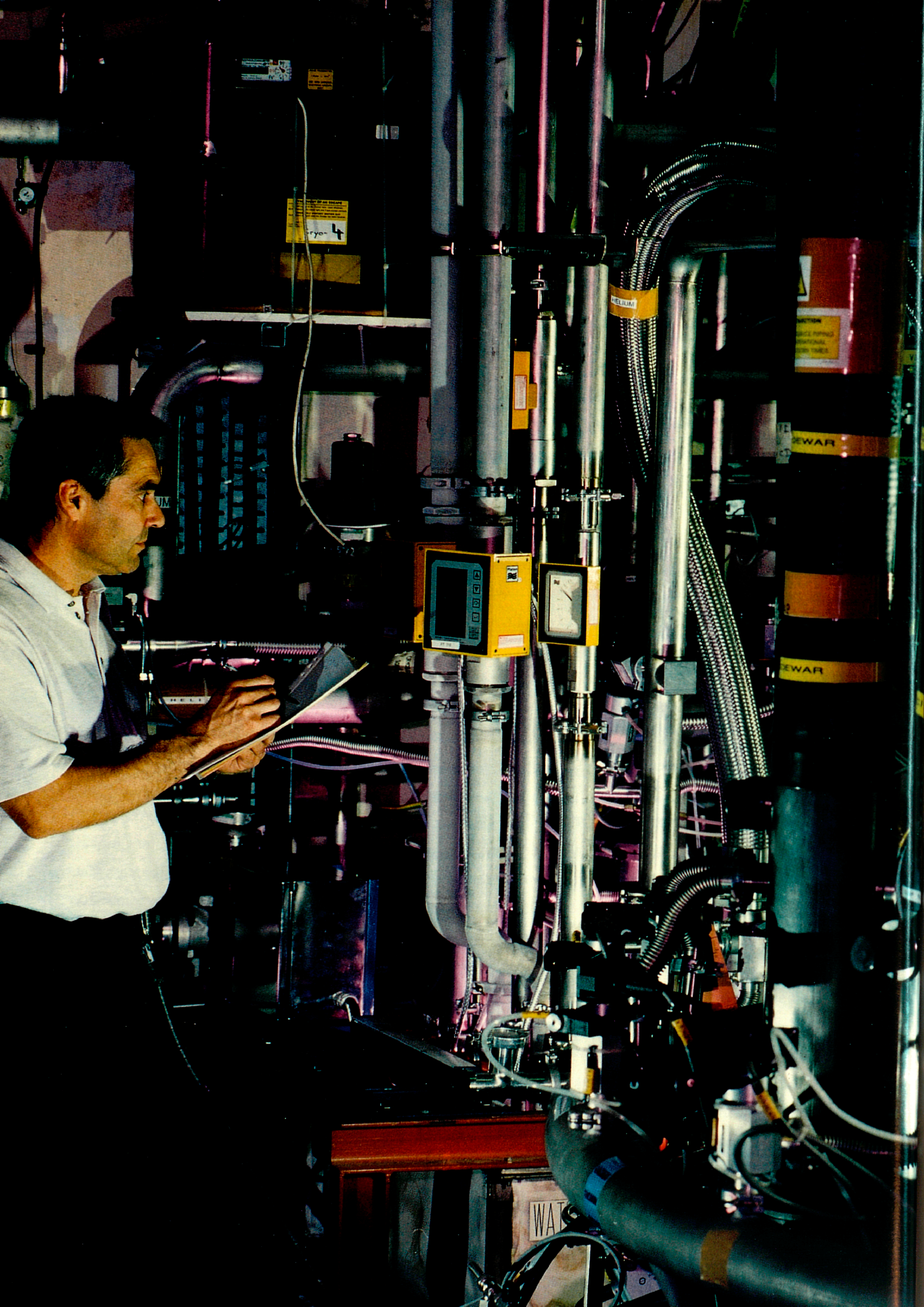
During the rest of 1997 and the first half of 1998, the Mark IIGB divertor will be tested with deuterium plasmas at high power. The design of the Mark IIGB provides flexibility to modify the target geometry with relative ease. The Programme Plan provides for two target geometries for Mark IIGB, together with a septum which may, or may not, be included to limit the communication between the inner and outer divertor legs and to absorb energy from energetic neutrals and photons.

Possible ways of improving JET's performance are under consideration, include increasing the toroidal magnetic field (to 4T), increasing the heating power (by ≈30%) and overcoming the performance limitations due to MHD instabilities.

Final Phase of D-T Operation (mid-1998 to end-1999)

A four month shutdown in 1998 will permit any necessary modifications to the divertor and final preparations for a further period of D-T operation (DTE-2). Normal manned in-vessel interventions will again be possible in this shutdown. The Mark IIGB divertor target structure is less flexible than Mark IIA with respect to the variety of equilibria which can be accommodated. Furthermore, its power handling capability in attached divertor operation is somewhat lower. Therefore, it may not be compatible with the highest plasma performance obtained in JET, such as the low density, high magnetic shear, hot-ion H-mode of operation. This must be tested experimentally and, if it proves to be the case, it will be possible to re-install Mark IIA (for DTE-2) following the completion of the Mark IIGB studies. During late-1998 and early-1999, the experimental programme will continue by optimising plasma performance in deuterium in preparation for DTE-2.

DTE-2 is scheduled to take place during the remainder of 1999. DTE-2 experiments could last up to eight months and could produce up to 5 x 10^{21} neutrons. Actual neutron production, within this upper limit, will be reassessed in the light of the experience with D-T operations on JET and TFTR. Every effort will be made to reduce this upper limit, while still satisfying JET's role in supporting ITER and the world fusion programme. In this way, the activation of the JET structure would be kept as low as possible compatible with fulfilling the required objectives.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Members and Organisation

Members

The JET Joint Undertaking has the following Members:

The European Atomic Energy Community (EURATOM);

The Belgian State, acting for its own part ('Laboratoire de Physique des Plasmas de l'École Royale Militaire - Laboratorium voor plasma-physica van de Koninklijke Militaire School') and on behalf of the Université Libre de Bruxelles' ('Service de physique statistique, plasmas et optique non-linéaire de l'ULB'); and of the 'Centre d'Études de l'Energie Nucléaire (CEN)/ 'Studiecentrum voor Kernenergie' (SCK);

The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain;

The Commissariat à l'Énergie Atomique (CEA), France;

The 'Ente per le Nuova Tecnologie, l'Energia e l'Ambiente' ('ENEA') representing all Italian activities falling within the Euratom Fusion Programme including that of the 'Consiglio Nazionale delle Ricerche', (CNR);

The Hellenic Republic, Greece;

The Forskningscenter Risø (Risø), Denmark;

The Grand Duchy of Luxembourg, Luxembourg;

The Junta Nacional de Investigaçao Cientifica e Tecnológica (JNICT), Portugal;

Ireland;

The Forschungszentrum Jülich GmbH (KFA), Germany;

The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Germany;

The Swedish Natural Science Research Council (NFR), Sweden;

The Swiss Confederation, Switzerland;

The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands;

The Technology Development Centre Finland (TEKES);

The United Kingdom Atomic Energy Authority (UKAEA), Host Organisation.

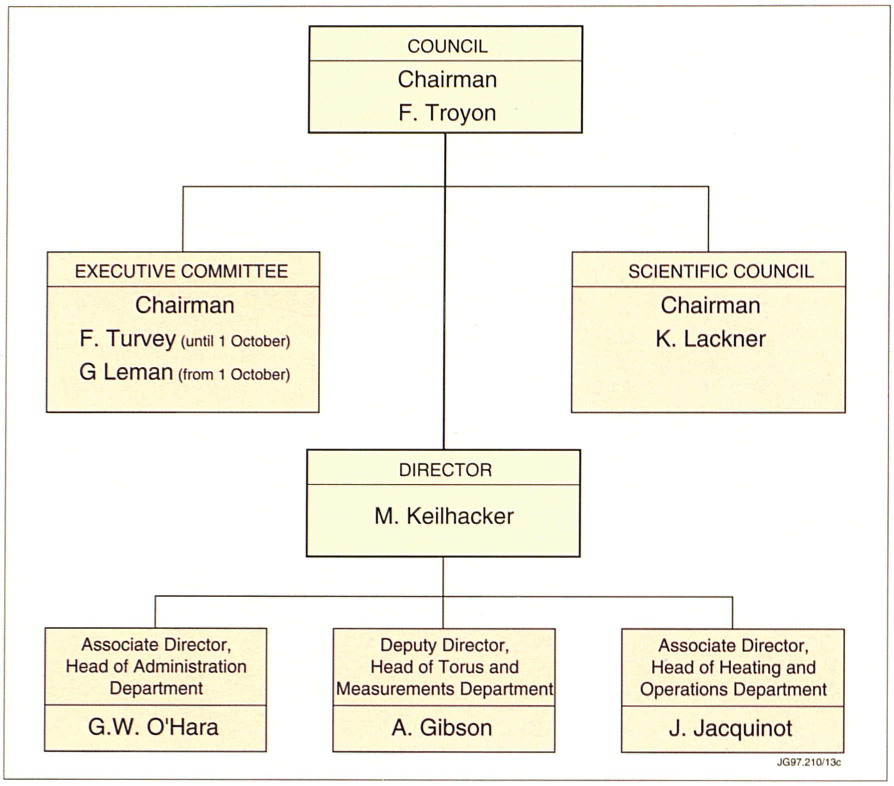


Fig.34: Overall Project Structure

Management

The JET Joint Undertaking is governed by Statutes which were adopted by the Council of the European Communities on 30 May 1978. The organs of the Joint Undertaking are the JET Council and the Director of the Project. The JET Council is assisted by the JET Executive Committee and is advised by the JET Scientific Council (see Fig.34).

JET Council

Each member of the Joint Undertaking is represented on the JET Council, which is required to meet at least twice yearly. The Council is responsible for the management of the Joint Undertaking and for:

- Nomination of the Director and Senior Staff of the Project with a view to their appointment by the Commission or the Host Organisation as appropriate;
- Approval of the annual budget, including staffing, the Project Development Plan and the Project Cost Estimates;
- Ensuring collaboration between the Associated Laboratories and the Joint Undertaking in the execution of the Project, including the establishment of rules on the operation and exploitation of JET.

Three meetings of the JET Council were held during the year: on 20th-21st March, 20th-21st June and 16th-17th October1996. The membership of the JET Council is shown in Appendix I.

JET Executive Committee

The JET Executive Committee is required to meet at least six times a year. Its functions include:

- Advising the JET Council and the Director of the Project on the status of the Project on the basis of regular reports;
- Commenting and making recommendations to the JET Council on the Project Cost Estimates and the Draft Budget, including the establishment of staff, drawn up by the Director of the Project;

- Approving, in accordance with the rules on the award of contracts established by the JET Council, the tendering procedure and the award of contracts;
- Promoting and developing collaboration between the Associated Laboratories and the Joint Undertaking in the execution of the Project.

The membership of the JET Executive Committee is shown in Appendix II. The Committee met six times during 1996: on 8th-9th February, 25th-26th April, 11th July, 26th-27th September, 31st October-1st November and 5th-6th December 1996.

JET Scientific Council

The Statutes confer the following functions on the JET Scientific Council:

- Upon the request of the JET Council, to advise on scientific and technical matters, including proposals involving a significant change in the design of JET, its exploitation, and its long-term scientific implications;
- To perform such other tasks as the JET Council may request it to undertake.

The Scientific Council met three times during the year: on 17th-18th January, 14th-15th May and 24th - 25th September 1996.

The JET-SC Chairman reported to the JET Council, on three occasions, on:

- the results of the 1996 Experimental Campaign, including implications for DTE-1;
- JET operations with reversed magnetic shear;
- the status of technical preparations and the main experiments planned for the DTE-1 phase;
- the proposal to upgrade the neutral beam and ion cyclotron resonance frequency heating power on JET; and
- the proposal to upgrade the toroidal magnetic field system for JET operation at 4 Tesla.

During 1996, the Joint JET and JET Scientific Council Reliability Assessment Group reported on the technical risks of JET operation at toroidal fields above 3.45 Tesla.

The full Scientific Council membership is detailed in Appendix III.

Host Organisation

The United Kingdom Atomic Energy Authority, as the Host Organisation for the JET Joint Undertaking, has made available to the Joint Undertaking, the land, buildings, goods and services required for the implementation of the Project. The details of such support, as well as the procedures for co-operation between the Joint Undertaking and the Host Organisation, are covered by a 'Support Agreement' between both parties. In addition to providing staff to the JET team, the Host Organisation provides support staff and services, at proven cost, to meet the requirements of the JET Project.

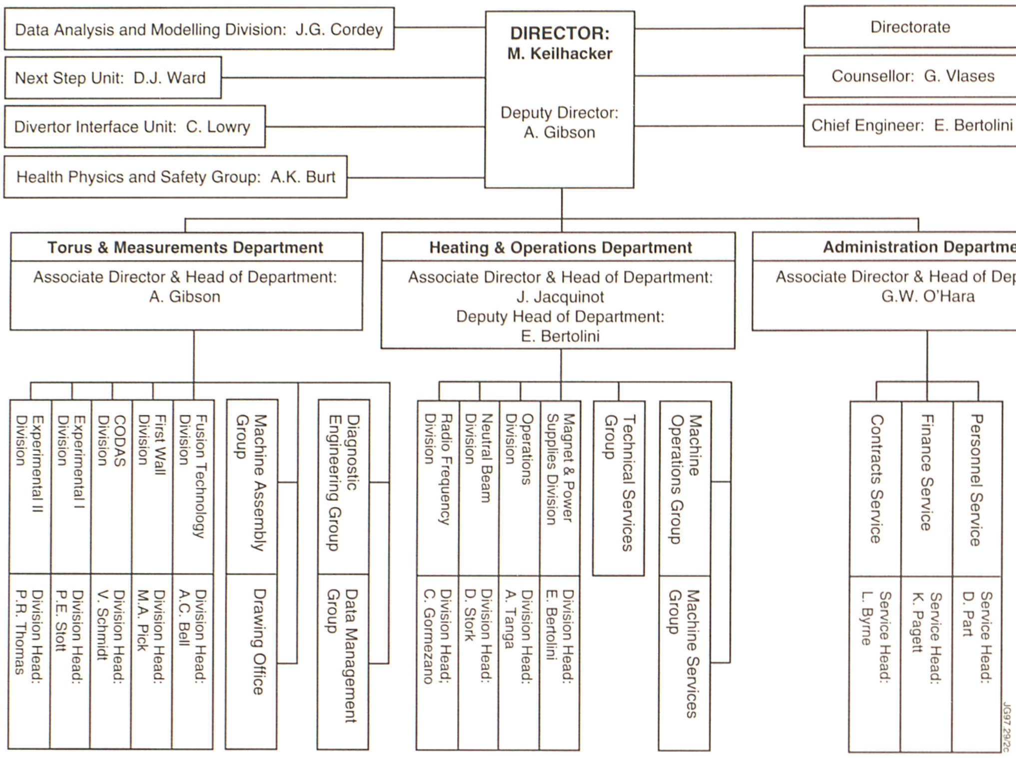


Fig.35: JET Departmental and Divisional Structure

Project Team Structure

The Director of the Project

The Director of the Project, Dr. M. Keilhacker, is the chief executive of the Joint Undertaking and its legal representative. He is responsible to the JET Council for the execution of the Project Development Plan, which specifies the programme, and for the execution of all elements of the Project. The Project Development Plan covers the whole term of the Joint Undertaking and is regularly updated. The Director is also required to provide the JET Council and other subsidiary bodies with all information necessary for the performance of their functions.

Internal Organisation

The internal organisation of the Project consists of three Departments and the Directorate. The three Departments are: Torus and Measurements Department; Heating and Operations Department; and Administration Department. The Project Departmental and Divisional structure is shown in Fig.35. Further details of the Technical Departments is given in the 1996 JET Progress Report.

Directorate

The Heads of the Departments report to the Director of the Project and together with the Director form the JET Directorate. Various special functions are carried out by the Director's Office. The Internal Audit Office monitors the financial activities and provides advice on accounting and control procedures as well as maintaining links with the Court of Auditors. The Project Control Office is responsible for financial planning and for the preparation of the Project Development Plan and Project Cost Estimates. The JET Council Secretariat provides Secretarial Services to the JET Council and to the Executive Committee and also to the JET Project Board.

Within the Directorate are three technical units (The Next Step Unit, The Divertor Interface Unit , and Health Physics and Safety Group), one Division (The Data Analysis and Modelling Division) and a Chief Engineer, reporting directly to the Director.

Torus and Measurements Department

The Torus and Measurements Department has overall responsibility for the performance capacity of the machine: this includes enhancements directly related to this (excluding heating) and the long term planning associated with integration of these elements to achieve ultimate performance. The Department is also responsible: for fusion technology requirements for the active phase including tritium handling and processing; for construction and operation of necessary measurement diagnostic systems and the interpretation of experiment data; and for data systems comprising data control, acquisition and management. The main functions of the Department are:

- to design, procure and implement enhancements to the JET device;
- to provide and maintain clean conditions inside the vessel which lead to high quality plasma discharges;
- to conceive and define a set of coherent measurements;
- to be responsible for construction of necessary diagnostics;
- to be responsible for diagnostics operation, quality of measurements and definition of plasma parameters;
- to organise and implement data acquisition and computing;
- to design and develop remote handling methods and tools to cope with JET requirements;
- to design and construct facilities for handling tritium and for waste management.

The Department consists of five Divisions (First Wall Division, Fusion Technology Division, Control and Data Acquisition System Division (CODAS), Experimental Division 1 (ED1), and Experimental Division 2 (ED2)) and four Groups (Machine Assembly, Diagnostic Engineering, Data Management and the Drawing Office).

Heating and Operations Department

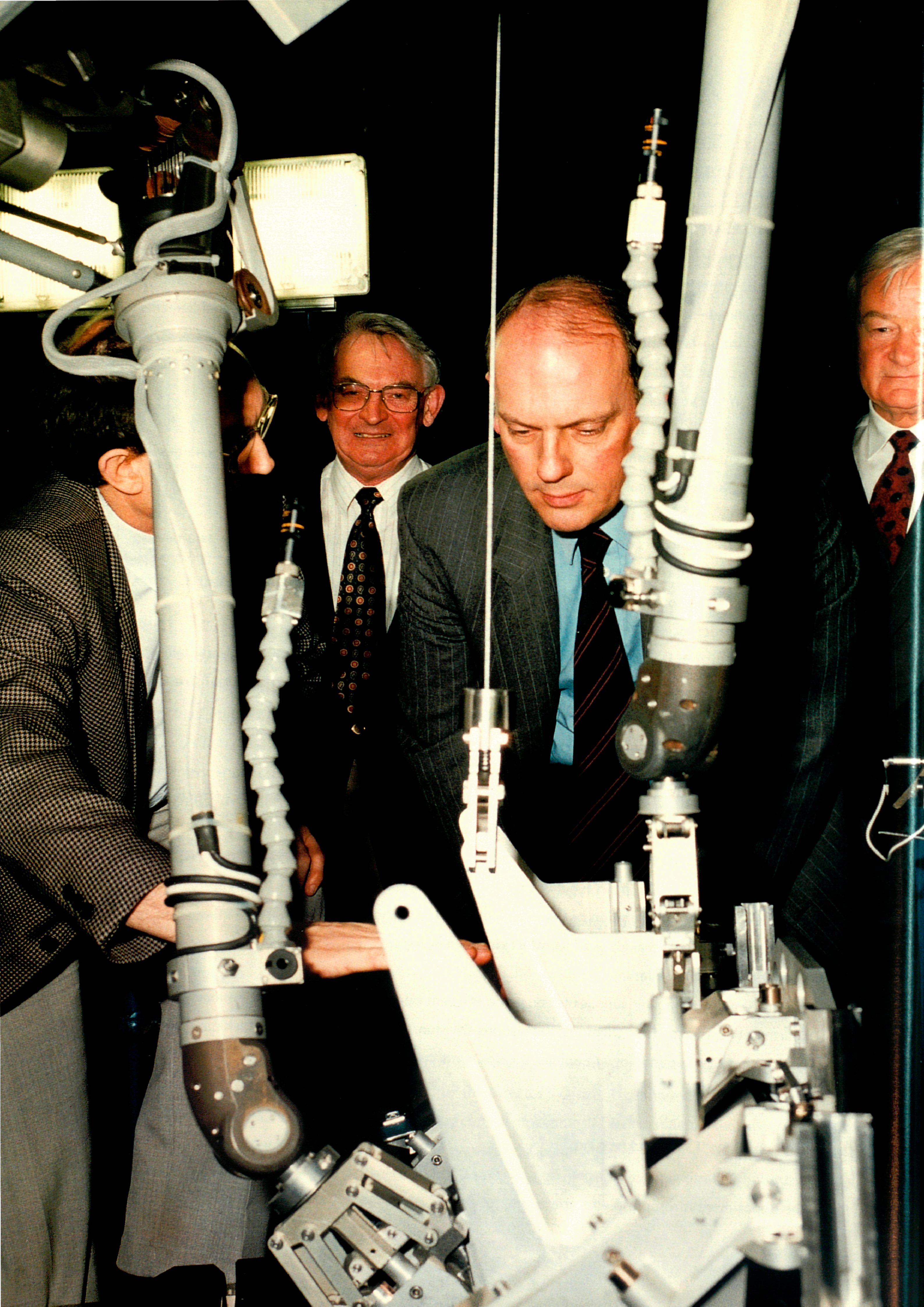
The overall responsibility of the Heating and Operations Department is for the efficient and effective day-to-day operation of the machine. In addition, the Department has responsibility for plasma heating and auxiliary equipment and related physics; the design and operation of power supplies as well as contributing to the execution and evaluation of JET's experimental programme. The main functions of the Department are:

- preparing and co-ordinating operation of the machine across Departments and Divisions;
- heating and current drive and analysis of its effects in the plasma;
- plasma fuelling, including pellet injection;
- designing and employing power supplies for ensuring efficient operation and control of the machine.

The Department consist of four Divisions (Operations Division, Neutral Beam Heating Division, Radio Frequency Heating Division, and Magnet and Power Supplies Division) and three Groups (Machine Operations, Machine Services and Technical Services).

Administration Department

The Administration Department is responsible for providing Contracts, Finance and Personnel services to the Project. In addition, the Department is responsible for the administration of Publications and Public Relations Groups.



Administration

Introduction

The three main aspects of JET's administration - Finance, Contracts and Personnel - are reported in this section. There are also contributions on Safety and Health Physics, Public Relations and Publications Groups.

Finance

The initial budgets for 1996 were approved at 74.35MioECU for Commitments and 76.66MioECU for both Income and Payments. The Commitments Budget included an Operations Reserve of 2.21MioECU which was released during 1996 by the JET Council and used to finance work on the enhancement of the toroidal field power supplies.

The Commitments and Payments Budgets each are divided into two phases of the Project - Extension to Full Performance and the Operational Phase; subdivisions distinguish between investment, operating, and personnel costs, each with further detailed cost codes.

Commitments

Of the total final appropriations in 1996 of 82.97MioECU (including 8.62MioECU brought forward from previous years), 74.20MioECU was committed and the balance of 8.77MioECU was available for carrying forward to 1997. The details of the commitment appropriations available (Table 5) and of the amounts committed in each Phase during the year (Table 6) are summarised as follows:

- In the extension to Full Performance Phase 0.48MioECU was committed leaving 0.45MioECU commitment appropriations not utilised at 31 December 1996, to be carried forward to 1997.
- In the Operational Phase, 73.72MioECU was committed leaving a balance of 8.32MioECU to be carried forward to 1997.

COMMITMENT APPROPRIATIONS	MioECU
FINAL COMMITMENTS BUDGET FOR 1996	74.35
AMOUNTS BROUGHT FORWARD FROM PREVIOUS YEARS.	8.62
	82.97
COMMITMENTS MADE DURING THE YEAR	74.20
BALANCE OF APPROPRIATIONS AT 31 DECEMBER 1996 AVAILABLE FOR USE IN 1997	**8.77**

Table 5: Commitment Appropriations for 1996

Income and Payments

The actual income for 1996 was 76.46 MioECU to which was added 0.30MioECU available appropriations brought forward from previous years giving a total of 76.76 MioECU. The 0.10MioECU excess income over budget is carried forward to be offset against Members' future contributions. Total payment appropriations for 1996 were 83.40MioECU; payments in the year amounted to 78.92MioECU; 1.95MioECU was transferred from the Special Account and will be offset against Members' future contributions. The balance of 2.53MioECU was transferred to the Special Reserve Account to meet commitments outstanding at 31 December 1996. (Payments are summarised in Tables 6 and 7).

Contributions from Members

The budget for Members' contributions was 75.26 MioECU (see Table 8) funded as follows:

- 80% from the general budget of the European Atomic Energy Community (Euratom);
- 10% from the UK Atomic Energy Authority as Host Organisation;
- 10% from members who have Contracts of Association with Euratom in proportion to the previous year's contribution from Euratom towards the cost of their Association Contracts.

		COMMITMENTS		PAYMENTS	
BUDGET HEADING		BUDGET APPRO-PRIATIONS MioECU	OUTTURN MioECU	BUDGET APPRO-PRIATIONS MioECU	OUTTURN MioECU
PHASE 2	**EXTENSION TO FULL PERFORMANCE**				
TITLE 1	PROJECT INVESTMENTS	0.93	0.48	0.77	0.76
PHASE 3	**OPERATIONAL**				
TITLE 1	PROJECT INVESTMENTS	4.31	3.02	3.06	2.45
TITLE 2	OPERATING COSTS	30.75	27.02	31.29	29.96
TITLE 3	PERSONNEL COSTS	46.98	43.68	48.28	45.75
TOTAL PHASE 3		82.04	73.72	82.63	78.16
PROJECT TOTAL - ALL PHASES		**82.97**	**74.20**	**83.40**	**78.92**

Table 6: Commitments and Payments for 1996

Table 7: Income and Payments for 1996

INCOME AND PAYMENTS	MioECU	
INCOME		
BUDGET FOR 1996		76.66
INCOME RECEIVED DURING 1995		
(I) MEMBERS' CONTRIBUTIONS	75.26	
(II) BANK INTEREST	1.11	
(III) MISCELLANEOUS	0.09	
(IV) UNUSED APPROPRIATIONS BROUGHT FORWARD FROM PREVIOUS YEARS	0.30	
TOTAL INCOME		76.76
VARIATION FROM BUDGET		0.10
REPRESENTING:		
INCOME IN EXCESS OF BUDGET CARRIED FORWARD FOR OFFSET AGAINST MEMBERS' FUTURE CONTRIBUTIONS		0.10
PAYMENTS		
BUDGET FOR 1996	76.66	
AMOUNTS AVAILABLE IN THE SPECIAL ACCOUNT TO MEET OUTSTANDING COMMITMENTS AT 31 DECEMBER 1995.	6.74	
TOTAL AVAILABLE APPROPRIATIONS FOR 1996		83.40
ACTUAL PAYMENTS DURING 1996	78.92	
FROM SPECIAL ACCOUNT TRANSFERRED TO INCOME.	1.95	
		80.87
UNUTILISED APPROPRIATIONS AT 31 DECEMBER 1996 CARRIED FORWARD IN THE SPECIAL ACCOUNT TO MEET OUTSTANDING COMMITMENTS AT THAT DATE.		2.53

Bank Interest

During the year, funds are normally received on a quarterly basis in respect of Members' contributions and intermittently for other items. Therefore, the Project has funds not immediately required for the discharge of its commitments; these funds are placed on deposit accounts at market interest rates. During 1996, earned interest amounted to 1.11MioECU.

Table 8: Percentage Contributions to JET for 1996, based on the Euratom participation in Associations' Contracts for 1996

MEMBER	%	Mio ECU
EURATOM	80.0000	60.21
BELGIUM	0.1886	0.14
CIEMAT, SPAIN	0.4324	0.32
CEA, FRANCE	1.9739	1.49
ENEA, ITALY	1.5788	1.19
RISO, DENMARK	0.0779	0.06
LUXEMBOURG	0.0000	0.00
JNICT	0.0780	0.06
KFA, GERMANY	0.7157	0.54
IPP, GERMANY	2.5656	1.93
FZK, GERMANY	0.7171	0.54
NFR, SWEDEN	0.2318	0.17
SWITZERLAND	0.5433	0.41
FOM, NETHERLANDS	0.3731	0.28
TEKES, FINLAND	0.0240	0.02
UKAEA	10.4998	7.90
	100.0000	**75.26**

FINANCIAL TRANSACTIONS	MioECU
CUMULATIVE COMMITMENTS	1,640.8
CUMULATIVE PAYMENTS	1,623.7
UNPAID COMMITMENTS	17.1
AMOUNT CARRIED FORWARD IN THE SPECIAL ACCOUNT	2.5
AMOUNT AVAILABLE FROM 1993, 1994 AND 1995 TO SET OFF AGAINST FUTURE CONTRIBUTIONS FROM MEMBERS	2.4

Table 9: Summary of Financial Transactions at 31 December 1996

Appropriations from Earlier Years

Unused payment appropriations and excess income over budget of 0.30 MioECU arising in 1993 and 1994 were transferred to income in 1996.

Summary

Table 9 summarises the financial transactions of the JET Joint Undertaking as at 31 December 1996. These have yet to be audited. The final audited accounts will be published in due course.

Contracts Service

Contracts Activity

In 1996, contract activity took place as set out in Table 10.

Many of the larger contracts involved advance and retention payments for which bank guarantees were required by JET. The total value of guarantees held as at 31 December 1996 was 1.0MioECU.

Imports and Exports Services

Contracts Service is also responsible for the import and export of JET goods. 525 imports and 235 exports were handled in 1996. There were also 1384 issues of goods to UK firms. The total value of issues to all countries for the year was 3.067MioECU.

Stores Organisation

The bulk of JET material is procured on a "just in time" basis and the stores organisation provides a receipts and delivery service for this material to the Project. The total number of such receipts in 1996 was16,864.

FORMAL TENDER	SUPPLY	SERVICE	PERSONNEL	TOTAL
ACTIONS: NUMBER	76	39	23	138

CONTRACTS PLACED	MAJOR (>75KECU)	MINOR (<75KECU)	DIRECT ORDERS	AMENDMENTS AND WARRANTS	TOTAL
QUANTITY	67	3,293	11,184	855	15,399
VALUE MIOECU	11.514	12.706	2.358	31.186	57.764

Table 10: Formal Tender Actions and Contracts placed during 1996

Table 11: Allocation of JET Contracts

COUNTRY	TOTAL OF KECU	% OF TOTAL
UK	664,736	59.27
GERMANY	168,014	14.98
FRANCE	91,927	8.20
ITALY	60,077	5.36
SWITZERLAND	43,213	3.85
DENMARK	13,463	1.20
NETHERLANDS	18,517	1.65
BELGIUM	12,239	1.09
SWEDEN	7,234	0.65
IRELAND	1,049	0.09
FINLAND	954	0.09
OTHERS	39,992	3.57
TOTALS	**1,121,415**	**100.00**

Administration of Contracts

The distribution of contracts between countries is shown in Tables 11 and 12. Table 11 includes all contracts with a value of 10,000 ECU and above placed prior to 1984, together with all contracts placed during the period 1984-96. Table 12 is an allocation of "high-tech" contracts, which is based on the figures shown in Table 11 but excludes all contracts below 5,000 ECU and contracts covering civil works, installation, pipework, consumables (including gases), maintenance operations and office equipment (including PCs).

Personnel Service

Staffing Position

JET's staffing position has remained constant this year (see Table 13). Fifteen team posts were vacated in 1996 by staff departures (4.3% of strength). Twelve UKAEA staff left, which included one to ITER and three retirements. Retirement accounted for the departures of the Euratom and DGXII staff.

Table 12: Allocation of JET "High-Tech" Contracts

COUNTRY	TOTAL OF KECU	% OF TOTAL
UK	148,162	28.11
GERMANY	146,379	27.77
FRANCE	80,503	15.28
ITALY	52,235	9.91
SWITZERLAND	35,249	6.68
DENMARK	7,448	1.41
NETHERLANDS	17,128	3.26
BELGIUM	5,080	0.96
SWEDEN	4,738	0.90
IRELAND	426	0.08
OTHERS	29,682	5.64
TOTALS	**527,030**	**100.00**

	DEC 1994	DEC 1995	DEC 1996
UKAEA	218.5	227.5	229.5
EURATOM	127.0	117.0	115.0
DGXII	6.0	6.0	5.0
TOTAL	**351.5**	**350.5**	**349.5**

Table 13: JET Staffing Position over 1994-96

New UKAEA staff assignments to the Project filled fourteen vacant posts. There were no new Euratom members of staff. Contract personnel on individual contracts, charged to Title 3 of the JET budget, numbered 202.5 at 31st December 1996.

Following approval in May 1996 for the prolongation of the JET Joint Undertaking to 31st December 1999, the JET Council asked the JET Executive Committee to begin a top-down review of personnel costs at JET and consider how the situation could be managed as the end of the Project approached. During 1996, the sub-committee established by the JET Executive Committee collected information and began to draft its report. The sub-committee met the Staff Representatives Committee as part of its information-gathering activity. The sub-committee's report will be presented to the JET Executive Committee and JET Council in early 1997. Figure 36 shows the composition of the JET team by nationality.

Promotions

In 1996, three existing team staff, 1 UKAEA and 2 Euratom, were selected to fill posts at Group Leader level. Twenty-nine team staff were promoted to a higher grade following the annual promotion exercise.

Conditions of Service

Team staff received the usual pay rises, and UKAEA or Euratom pay increments and bonuses were awarded, following reviews of staff performance.

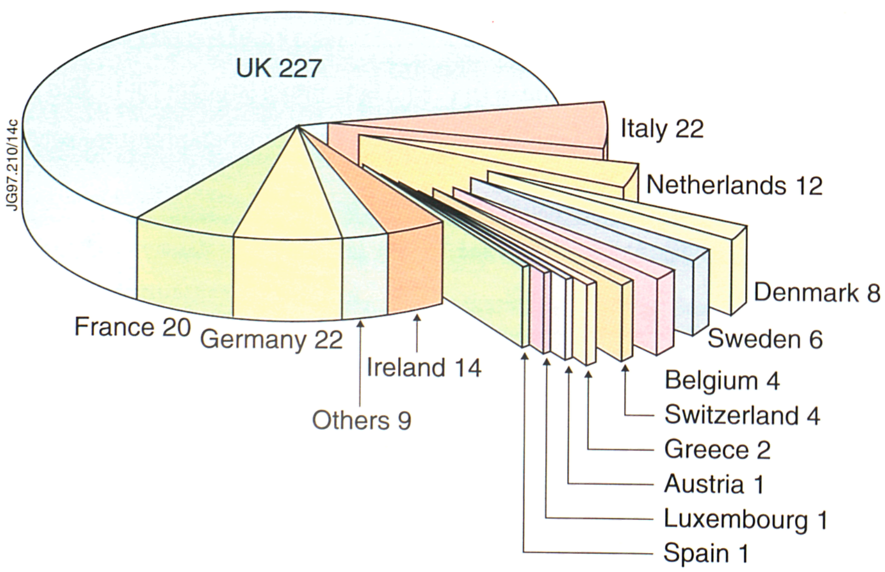


Fig.36: Composition of JET Team by nationality

A group incentive bonus scheme was introduced for UKAEA staff at Band and PMG1 level. JET management agreed to participate in the scheme and set a number of management and technical targets. The scheme allows for a bonus of up to 5% of salary to be paid calculated on group performance against these targets. Bonuses of 2.78% of salary were paid to 63 eligible staff at a cost of 90.1 KECU.

The UKAEA Retention of Experience Allowance was paid to 219 eligible UKAEA team staff in post on 31 December 1996, at a cost of 1.2 MioECU.

The Court of First Instance of the European Communities delivered its judgement on 12 December 1996 regarding the cases of 71 UKAEA staff claiming the status of members of the temporary staff of the Commission. The implications of this judgement for the Project are being examined.

Staff Relations

In 1996, the JET Director and other representatives of the JET Management had regular and frequent meetings with Staff Representatives. Information was exchanged, particularly on JET's future and the financial position and briefing sessions were provided for all staff on JET's public relations strategy, and JET's financial position. Other matters discussed included working patterns, staffing issues, the working environment and site services (e.g. the need for Sunday working).

As in previous years, the SRC made a presentation to the JET Council on issues of concern to them. The paper in October 1996 referred to the status of JET staff and the Project's short-term future, the future careers of staff and the representational role of the SRC. JET supports social activities among staff by subsidising events and activities. The Social, Sports and Cultural Committee (SSCC) was granted a budget of £20,000 in 1996 to allocate to staff activities and clubs.

In May 1994, the European Parliament formally voted to make available from the Community budget, 2MioECU for disbursement to UKAEA staff assigned to JET. These disbursements were to be part of a package of measures to help resolve the UKAEA staff petition to the European Parliament. The JET Council agreed that JET could make the disbursements, acting as an agent, outside its normal budget. In August 1996, UKAEA lodged a formal appeal on behalf of JET against the UK Department of Social Security ruling that there is a liability for National Insurance contributions. This appeal is still pending.

Consultants

Ten consultants contributed 332.5 man-days of scientific/technical support work. One third of these days were attributable to a Finnish consultant who became an Assigned Associated Staff member in July 1996 following Finland becoming a member of JET.

LABORATORY	MAN-YEARS 1996	MAN-YEARS 1995
UKAEA (UK)	13.6	12.5
NFR (SWEDEN)	4.9	3.0
IPP/KFK (GERMANY)	3.2	4.0
CEA (FRANCE)	2.7	1.6
ENEA (ITALY)	2.2	2.5
JNICT (PORTUGAL)	2.0	1.4
KFA (GERMANY)	1.6	0.7
CRPP (SWITZERLAND)	1.6	1.4
ERM (BELGIUM)	0.6	0.0
CIEMAT (SPAIN)	0.6	0.5
TEKES (FINLAND)	0.5	0.0
FOM (THE NETHERLANDS)	0.1	0.1
TOTAL	**33.6**	**27.7**

Table 14: Staff assignments from Associated Laboratories during 1995-96

Assigned Associate Staff

The Associations provided a total of 33.6 man-years of effort to JET during 1996, an increase of 5.9 man-years over 1995. This increase is in part attributable to preparations for DTE1 and in part to provide particular expertise. Tables 14 and 15 show the contributions made by the Associations in 1996 and the distribution of the Assigned Associate Staff within the Project.

Visiting Scientists

JET selects Visiting Scientists to be appointed through the UKAEA as Temporary Research Associates. During 1996, two new appointments were made, of which one was a non-EU national. There were three Visiting Scientists at the end of the year.

Post Graduate Researchers

At the end of 1996 there were 18 post-graduate researchers at JET under various schemes, including the Human Capital and Mobility Scheme and the Co-operative Awards in Science and Engineering (CASE).

A JET Research Associate Scheme was set up to replace the JET Fellowship Scheme. Its aim is to provide opportunities for post-graduate students and researchers who are nationals of the European Union and Euratom to further and improve their training in a range of scientific activities.

Students

JET supported 31 students in 1996, 21 of whom undertook long term placements of 13 weeks or more. In 1996, JET also became registered as an Approved Work Experience Provider. As a result, 19 secondary pupils from local schools spent,

DEPARTMENT	MAN-YEARS 1996	MAN-YEARS 1995
TORUS AND MEASUREMENT	18.1	13.6
HEATING AND OPERATIONS	9.0	7.5
DIRECTORATE AND DATA ANALYSIS AND MODELLING	6.5	6.6
TOTAL	**33.6**	**27.7**

Table 15: Assigned Staff within the Project during 1995-96

on average, two weeks gaining work experience relevant to their examination studies. In addition, JET continued to support placements under the CSN agreement with the French government, whereby military service can be carried out in a non-military role at a research establishment.

Training

During 1996, approximately 60 staff attended short external training courses in order to acquire specific required skills.

Approximately 130 team staff received language tuition in French, German, Italian and Spanish. Twelve candidates passed the London Chamber of Commerce and Industry examinations in the relevant language, a success rate of 83%.

Seven staff are supported by JET on long-term courses for professional development.

Approximately 130 JET personnel (from all categories) attended major Conferences or Workshops during the year.

Health Physics and Safety

The Director is responsible for safety and is required by the JET Statutes to undertake all organisational measures to satisfy relevant safety requirements. JET continues to meet all the requirements of relevant UK and EC legislation and, in accordance with the Host Support Agreement, JET complies with the safety regulations of the Host Organisation. Responsibilities for Safety and Health Physics are discharged by the Health Physics and Safety Group which, following the dissolution of the Co-ordinating Staff Unit early in 1996, is within the Directorate.

Safety

The group provides a general safety service that incorporates safety related training, monitoring, co-ordination and planning of statutory inspections. It ensures there is an awareness of any legal requirements or changes to existing legislation. An important control measure that assists in ensuring all work is carried out safely, is the Work Permit and Safety Assessment procedure. The revised procedure introduced in June 1995 was subject to an audit during 1996 to identify strengths and weaknesses. As a result of the audit additional guidance was issued and the operation of the system continues to be monitored by the Safety Section.

JET's compliance with its Fire Certificate was examined during 1996 with all areas being inspected with the assistance of the Security and Emergency Service from Culham. No significant non-compliance was recorded and all actions from the survey are being addressed.

Safety related training followed the normal pattern for basic courses but with particular emphasis in 1996 on preparations for the Deuterium-Tritium operations. It was decided that all JET personnel should receive some training to at least be aware of the implications of D-T operations and two new courses were introduced. The first level of training was focussed on those staff who could be involved in tritium related operation and the second level aimed at all other staff to inform them of the programme and to make them aware of tritium. In addition, refresher training was provided to all classified radiation workers who had not attended any radiological training for three years. The numbers attending were 333 for the detailed tritium course, 443 attended the tritium awareness course and 322 attended either the basic or refresher radiological protection course.

Other safety related training was provided by 25 different topics with a total of 2485 (3095) attendees (the figures in brackets being the total in the previous year). Safety Induction 352 (530) continues to be the route for ensuring all staff are aware of the safety culture at JET.

Throughout the year, there were 121 (122) accidents reported to the Safety Section and all but three were minor. Seven accidents were reported under the "Reporting of Injuries, Diseases and Dangerous Occurrences Regulations" (RIDDOR) to the Health and Safety Executive because they resulted in absences from work exceeding 3 days. There were 5 (3) Incident Safety Review Panels set up by the Chief Engineer. The implementation of the recommendations made by these Review Panels are monitored by the Safety Section and reported at the regular JET Safety Working Group meetings that has representatives from all staff groups.

During 1996, new legislation entitled Construction Design and Management Regulations came into effect. The purpose of these regulations is to introduce Health and Safety Standards to improve the management of construction projects. The regulations are applied to all stages of construction, design, planning execution and maintenance. JET addressed the regulations by specialist instructions to those sections most likely to be affected.

Health Physics

The section continues to provide a comprehensive routine service that includes radiological protection, occupational hygiene, dosimetry, beryllium analysis and environmental monitoring on and off the Culham site.

The Mark II Divertor shutdown involving in-vessel man entries was completed at the end of March. There was a shutdown during June with no in-vessel operations and a further intervention in October lasting about 4 weeks. For Torus interventions, the in-vessel radiation level determines the work schedule to ensure personal exposures remain controlled within JET's limits. The in-vessel radiation level at the start of the October shutdown was an average of 320 $\mu Sv\ h^{-1}$ but with localised high spots of 500 $\mu Sv\ h^{-1}$ at Octant No.3 in the area of the launcher. The maximum in-vessel radiation level for the start of the Mark II Divertor shutdown had been 125 $\mu Sv\ h^{-1}$.

Throughout the year, the Active Gas Handling Facility had completed a trace tritium followed by a full active commissioning of the plant involving an inventory of 3g of tritium. At all phases of the commissioning and subsequent maintenance, radiological monitoring of the area and personnel has indicated that no personal exposures from tritium had occurred.

The collective dose accrued as a result of all torus interventions was 0.182 man.Sv (0.241 man.Sv in 1995) with the total dose for all radiation work on the project at 0.215 man.Sv (0.251 man.Sv in 1995). The maximum individual dose arising from in-vessel work was 4.56 mSv (4.53 mSv) which was within the JET dose limitation policy and well below UK statutory limits.

The beryllium analysis laboratory continued to provide a service of measurement of the beryllium content of personal air samplers, that are worn by all personnel working in JET's beryllium controlled areas, and smears of surfaces to determine contamination levels. There were 8454 (12,392) personal air samples analysed all of which were below 2 $\mu g\ m^{-3}$, the maximum exposure limit specified in the Control of Substances Hazardous to Health Regulations. There were also 20,860 routine smears taken with a highest smear at 44,800 $\mu g\ m^{-2}$ taken in vessel at Octant No.5. In addition, 13,806 clearance smears were analysed with 76% below the limit of detection but the highest sample was 627 $\mu g.m^{-2}$.

Emergency Exercises

Following the exercise held in November 1995, the JET Emergency Plan was re-issued with amendments reflecting the lessons learnt.

In preparation for the tritium operational phase, personnel were re-appointed to key positions within the site emergency organisation and a table top exercise held to train participants. Engineers-in-Charge were given specific training to manange a potential site emergency. An external public address system was commissioned with the objective that in the event of an incident, personnel outside buildings be instructed to take shelter. Plans were prepared for a demonstration site exercise involving the public address system, which was held in early 1997. The exercise was witnessed by the Health and Safety Executive, the Environment Agency and representatives of the Director of Safety, UKAEA, who indicated that the exercise was successful.

Press and Public Relations

The revised JET Public Relations plan developed during 1995 was brought fully into effect during 1996. The main elements, all of which have progressed very successfully, were to make a new video about JET, updating and development of printed PR resources, refinement of the visits programme to achieve best return given limited management resources, accessing the goodness of JET suppliers to conduct PR activities of mutual benefit and beginning preparation of the PR arrangements for the D-T campaign in Summer 1997.

JET was pleased to receive 198 visiting groups during the year. Over 20% of these groups were from the media and other key targets for PR activities. Distinguished visitors included the Italian Ambassador to the UK, His Excellency Dr. Paolo Galli and the Science Counsellors from the London Embassies of France (Prof. H. Gibert), Italy (Prof. S. Aloj) and Japan (Mr. Y. Ito). Visits were made by many distinguished senior science administrators including M.Y. d'Escatha, Chairman of the French CEA, Prof. Sir John Cadogan, Head of the UK Research Councils, Dr. Martha Krebs of the US Department of Energy and Dr. S. Shimamoto, Director General of the JAERI at Naka in Japan. The members of the EU Fusion Evaluation Board visited JET in July as part of their review of the whole EU Fusion Programme.

Importance is attached to maintaining an open relationship with the political leadership of countries interested in fusion. Contacts with the London Embassies are important in this but visits were also received by a staff group from the US Congress, Mr. F. Jensen, the relevant Danish Minister, the UK Shadow Energy Minister, Mr. John Battle and the UK Minister for Europe, David Davies. JET was alsoe visited by Dr. Franco Malerba, the famous astronaut and Italian MEP.

Publications Group

The Publications Group provides a Graphics, Phototypesetting, Photographic and Reprographics service for the Project. The Group is led by the Publications Officer, who is also responsible for the clearance, production and distribution of all JET documents. In addition, the Group arranges attendance at major international Conferences, and prepares papers and posters for these Conferences and Meetings.

Conferences

JET provided contributions to a number of major meetings, as follows:

- 12th International Conference on Plasma Surface Interactions, St Raphael, France (May 1996) (2 Invited Papers, 17 Posters).
- 23rd European Physical Society Conference on Plasma Physics and Controlled Fusion, Kiev, Ukraine (June 1996) (2 Invited Papers and 24 Posters).

- 19th Symposium on Fusion Technology (SOFT-19), Lisbon, Portugal (September, 1996) (3 Invited Papers and 29 Posters).
- 16th IAEA Fusion Energy Conference, Montreal, Canada (October, 1996) (8 Orals and 2 Posters).
- 38th Annual Meeting of the American Physical Society - Division of Plasma Physics, Denver, USA (November 1996) (1 Invited Paper and 3 Posters).

In total, the Group prepared 134 Papers and 117 Posters for presentations to about twenty different Conferences throughout the world. Arrangements were also made by the Group for 121 participants to attend these major meetings during the year.

Publications

The Publications Office is responsible for the clearance and production of all JET presentations (including Journal Papers, Reports, Conference Papers, Poster Contributions, Lectures, etc). Throughout 1996, over 418 publications were cleared for external presentation.

During the year, 300 documents were published from the Project and the full list is included as an Appendix to the 1996 JET Progress Report. This total included 10 JET Reports, 60 JET Preprints, 5 JET Internal Reports, 2 JET Technical Notes and 6 JET Divisional Notes. All these documents are produced and disseminated by the Group on a wider international distribution. In addition, 114 papers were published in scientific Journals.

In total, the Group produced 3485 new illustrations and figures and took 5362 new photographs for publications and other disseminated material during 1996.

APPENDIX I
The JET Council

Member	Representative
The European Atomic Energy Community (EURATOM)	P. Fasella (to February) J. Routti (from February) C. Maisonnier (Vice-Chairman) (to November) U. Finzi (from November)
The Belgian State, acting for its own part ('Laboratoire de Physique des Plasmas de l'École Royale Militaire - Laboratorium voor plasma-physica van de Koninklijke Militaire School') and on behalf of the Université Libre de Bruxelles' ('Service de physique statistique, plasmas et optique non-linéaire de l'ULB'); and of the 'Centre d'Études de l'Energie Nucléaire (CEN)/'Studiecentrum voor Kernenergie' (SCK)	P.E.M. Vandenplas G. Michaux
The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain	A. Grau Malonda
Commissariat à L'Énergie Atomique (CEA), France	Mrs. C. Cesarsky D. Escande (to October) M. Chatelier (from October)
The 'Ente per le Nuova Tecnologie, l'Energia e l'Ambiente' ('ENEA') representing all Italian activities falling within the Euratom Fusion Programme including that of the 'Consiglio Nazionale delle Ricerche', (CNR); dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	R. Andreani C. Mancini
The Hellenic Republic (Greece)	A. Katsanos A. Grecos
The Forskningscenter Risø (Risø), Denmark	J. Kjems G. Bramsnaes (from March)
The Grand Duchy of Luxembourg (Luxembourg)	Mrs. S. Lucas (to March) J. Olinger (from March) R. Becker (to June) C. Bartocci (from June))
The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal	C. Varandas Mrs. M.E. Manso
Ireland	F. Turvey P. O'Neill (to May) L. Daly (from May)
The Forschungszentrum Jülich GmbH (KFA), Federal Republic of Germany	G. von Klitzing (to December) J.E. Vetter (from December)
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Federal Republic of Germany	K. Pinkau
The Swedish Natural Science Research Council (NFR), Sweden	G. Leman T. Hellsten
The Swiss Confederation	F. Troyon (Chairman) P. Zinsli
The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands	M.J. van der Wiel K.H. Chang
The Technology Development Centre Finland (TEKES)	S. Karttunen (from June) M. Korkiakoski (from June)
The United Kingdom Atomic Energy Authority (UKAEA)	J.R. Bretherton D.R. Sweetman (to September) D. Robinson (from September)

Secretary: J. McMahon, JET Joint Undertaking

APPENDIX II
The JET Executive Committee

Member	Representative
The European Atomic Energy Community (EURATOM)	J.P. Rager P.J. Kind (to February) U. Finzi (from February)
The Belgian State, acting for its own part ('Laboratoire de Physique des Plasmas de l'École Royale Militaire - Laboratorium voor plasma-physica van de Koninklijke Militaire School') and on behalf of the Université Libre de Bruxelles' ('Service de physique statistique, plasmas et optique non-linéaire de l'ULB'); and of the 'Centre d'Études de l'Energie Nucléaire (CEN)/'Studiecentrum voor Kernenergie' (SCK)	R. Vanhaelewyn P.E.M. Vandenplas
The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain	F. Manero A. Grau Malonda
Commissariat à L'Énergie Atomique (CEA), France	Mrs. P. Livanos R. Gravier (to March) B. Goudal (from April)
The 'Ente per le Nuova Tecnologie, l'Energia e l'Ambiente' ('ENEA') representing all Italian activities falling within the Euratom Fusion Programme including that of the 'Consiglio Nazionale delle Ricerche', (CNR); dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	A. Coletti F. Pecorella
The Hellenic Republic (Greece)	N. Chrysochoides
The Forskningscenter Risø (Risø), Denmark	Mrs. L. Grønberg V.O. Jensen
The Grand Duchy of Luxembourg (Luxembourg)	C. Bartocci (to June) M. Hoffman (from June)
The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal	J. da Costa Cabral F. Serra
Ireland	F. Turvey (Chairman to October) D. Taylor
The Forschungszentrum Jülich GmbH (KFA), Federal Republic of Germany	V. Hertling (to July) U. Nobbe (from July)
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Federal Republic of Germany	Mrs. I. Zilker-Kramer
The Swedish Natural Science Research Council (NFR), Sweden	G. Leman (Vice-Chairman to October, then Chairman) L. Gidefeldt
The Swiss Confederation	M. Tran S. Berthet
The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands	A. Verhoeven
The Technology Development Centre Finland (TEKES)	R. Salomaa (from June) M. Korkiakoski (from June)
The United Kingdom Atomic Energy Authority (UKAEA)	D.C. Robinson (to July) F. Briscoe (from July) T. Conlon

Secretary: J. McMahon, JET Joint Undertaking

APPENDIX III
The JET Scientific Council

Members appointed by the JET Council

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Staff Secretary: M.L. Watkins, JET Joint Undertaking